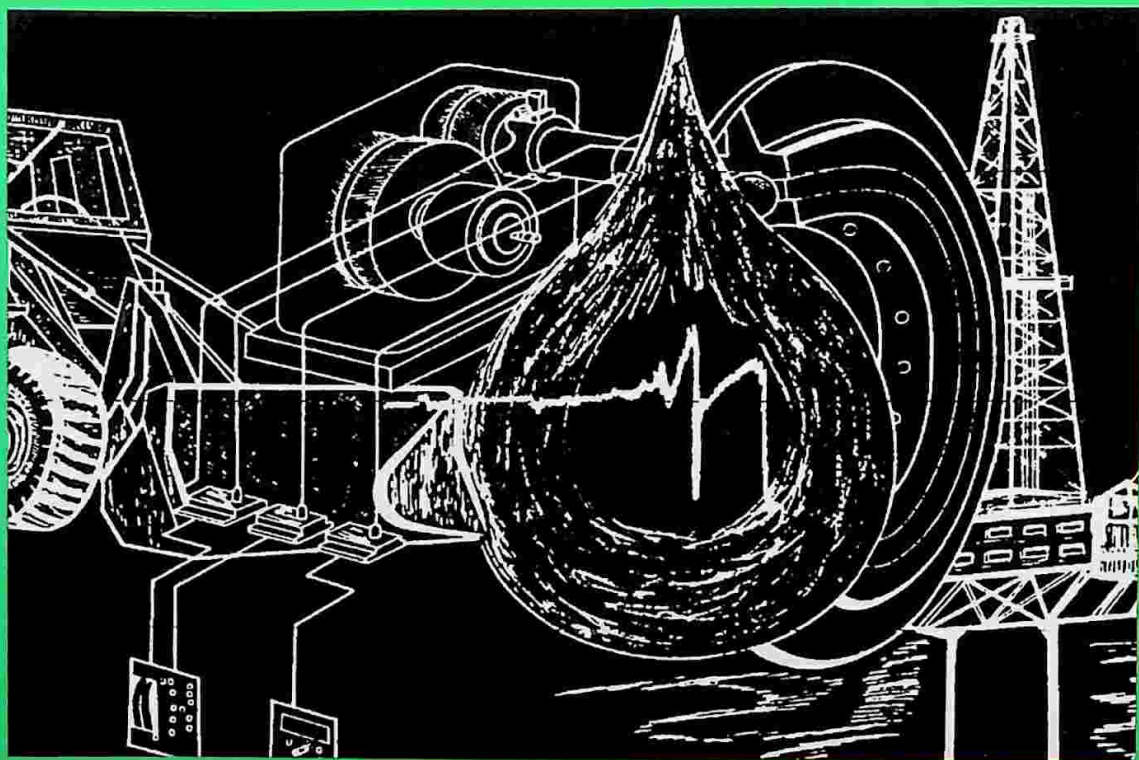


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Applying Satellite Communications Technology to Condition-Based Maintenance for Mobile Equipment

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Abstract

The advent of unattended sensor technologies has placed a particular challenge on data communication for machine surveillance monitoring. This challenge is magnified when mobile equipment and large geographic territories are involved. The use of satellite communications has recently been applied in an extensive condition-based maintenance program for a large fleet of railroad maintenance equipment. The satellite communications are a part of an integrated system of sensor, software and communications technologies. This paper describes the selection and application of sensors for the real-time monitoring of contamination in hydraulic fluid and engine oil. Also discussed will be onboard data collection electronics, onboard satellite transmission hardware and knowledge-based data analysis and exception reporting. The paper will be presented as a case study, and is believed to be the first of its kind for condition-based maintenance employing satellite communications technology.

1.0 INTRODUCTION

In the business realm today, an enterprise must achieve optimum efficiency in every area in order to survive in the marketplace. One area that concerns many is that of maintenance. Maintenance has been described as a business's "largest controllable expenditure."

If the expenditure of maintenance is controllable, how can it be controlled? The answer is very simple: root cause discovery and correction. If the source of the maintenance expense is found, the root cause can be investigated and corrected. In order to locate the root causes of equipment failures, equipment incurring maintenance cost must be monitored frequently. Monitoring root cause parameters allows the operator not only to monitor

and predict failure, but also enables him to extend and estimate equipment life. This type of condition-based maintenance combines the life-extension features of proactive maintenance with the failure prediction features of predictive maintenance. To actualize this type of maintenance program at a high level of effectiveness, a tremendous amount of data collection is required. This data must be collected, reported and stored quickly and easily. The most efficient method to accomplish this is the use of computer controlled sensors, coupled with data storage and trending capabilities.

In the case of mobile equipment, there is a barrage of added environmental and operational variables. Because of this, the need to monitor equipment health is more critical. However, monitoring mobile equipment can be very cumbersome. Imagine monitoring a fleet of mobile equipment operating in an area covering one half of North America. In this scenario, the use of satellite transmission for the transfer of sensor data is appealing. In the event that an integrated satellite communications system is economically justifiable and beneficial to reduce maintenance cost, countless additional data transfer opportunities are available. These opportunities include monitoring, messaging and mapping.

2.0 THE EFFECT OF THE ENVIRONMENT AND WORKLOAD ON EQUIPMENT LONGEVITY AND PERFORMANCE

Two main elements exist that affect the longevity and performance of fluid-dependent systems. These elements are workload and environment. Any failure or performance problem associated with a piece of equipment, aside from poor manufacturing, design and installation, can normally be traced to workload and environment. From a design standpoint, equipment should be engineered to withstand the workload it experiences in the environment in which it operates.

Environment and workload reduce equipment life with the help of two common deficiencies. These deficiencies can be described as the lack of knowledge and the lack of discipline. The lack of knowledge is a deficiency of maintenance knowledge and condition knowledge. In other words, not knowing how to maintain the equipment in the environment in which it operates and not knowing the condition of the equipment or what changes it may be experiencing. Lack of discipline is the failure to act or respond when the condition prescribes the need for maintenance activities. This lack of knowledge and discipline may not only be shared by the operator and maintenance manager, but also by the design engineer.

The environment and workload parameters can be broken down into several

items. These items include:

1. Atmospheric Hard Particle Contaminant Level
2. Internal System Contaminant Generation Level
3. Contaminant Abrasivity
4. Water Exposure Level
5. System Operating Pressure
6. Pressure/Flow Duty Cycle Severity

The most damaging environmental influence on a fluid-dependent system is hard particle contamination. According to Caterpillar, "dirt and contamination are by far the number one cause of hydraulic system failures." It has been estimated to be the source of over 80% of wear-related equipment failure. Since hard particles are the cause of such a high percentage of failure, the knowledge of these contaminant levels is of utmost importance in equipment maintenance. If contaminant target levels are defined, current contaminant level information can be used to determine maintenance actions and responses.

2.1 Equipment and Environment Specific Contaminant Ingestion

Contaminant ingestion is the migration of hard particle contaminants from the environment into a fluid-dependent system, such as a hydraulic system or power train. The level of ingestion that a specific piece of equipment experiences depends upon three items:

1. The environment in which it is placed
2. The condition that it creates in this environment
3. The protection that it retains against its environment

Equipment operating inside of an enclosed area (such as a factory) is protected from the outside elements such as rain, snow, extreme temperature and to some extent, exterior atmospheric hard particle contaminants (this will vary with the type of air filtration used in the ventilation system). In these situations, the focus can be placed on the particle levels generated in the plant and on the internal ingestion of the equipment.

In dealing with mobile equipment, there are several additional variables. These variables include the type of environment in which the equipment is working and the nature of work that it is performing. The type of environment will vary not only with region, but also with climate and weather. For example, if a piece of railroad work equipment is working in a region that contains sandy soil, it may experience more dust ingestion than a similar piece of equipment in a region where the soil contains a high amount of clay. However, identical pieces of equipment may experience less ingestion in a sandy region characterized by a humid climate than in a sandy region

characterized by a dry climate. Additionally, the ingestion level is affected by the weather on that particular day. For example, if the weather is overcast and the rainfall totals three inches, less ingestion will be expected.

Not only is the amount of ingestion important, but also the type of ingestion. Airborne particulate will vary in size, shape, hardness, angularity and abrasivity. These variables will affect the amount of damage done to critical component surfaces. For example, railroad work equipment operating on a rock ballast with a high granite content may risk more internal damage from ingestion than equipment operating on a rock ballast composed mainly of limestone.

Another variable to be considered is the condition that the equipment creates in its environment while it operates. This depends on the type of work that the equipment is designed to perform and the particular task that it is performing at any given time. For example, a ballast regulator, which is designed to plow and dress railway ballast, may generate a large cloud of dust composed of granite, limestone and/or soil particulate. All other things equal, this cloud will vary in size and shape depending on the nature and speed of the task being performed. A tamper, on the other hand, which is designed to align rail, does not usually stir up a visible cloud of dust. A dust cloud creates an additional environmental variable. This environmental variable will cause the engines on these two machines, although performing under similar workloads and conditions, to vary in performance and longevity. This variance, therefore, is dependent on the nature of the task being performed and is caused by the differing levels of contamination generated during operation. In the case described above, the ratio of the diesel engine life expectancy of the tamper to that of the ballast regulator can be as high as 4:1.

We can now see that longevity and performance can vary highly with environment, task and workload. If the knowledge of the variables and conditions affecting the performance and longevity of the equipment does not exist, proper action in terms of maintenance and upkeep cannot be performed.

3.0 A PROACTIVE MAINTENANCE APPROACH TO FLUID CONTAMINATION CONTROL

The primary objective of a new contamination control program must be to extend a machine's operating life (mean time between failure/overhaul). This activity is most commonly referred to as proactive maintenance. It has been stated that, "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." Furthermore, "proactive maintenance reflects a life extension mode capable of extending the service life of the machine because it addresses both

the detection and correction of root cause aberrations." This is illustrated below in figure 3.1.

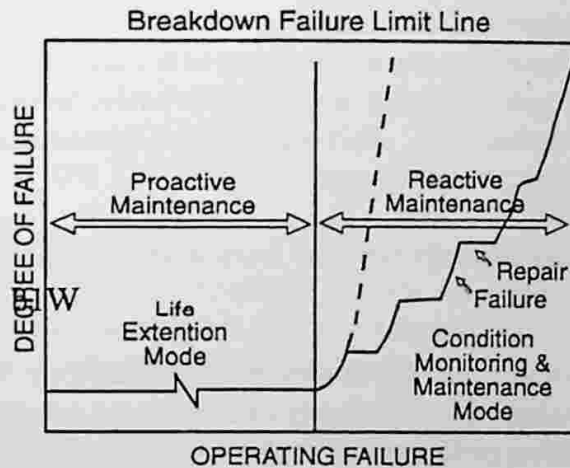


FIGURE 3.1

While extending machine life leads to many benefits, the most important is usually greater machine availability and utilization. Additionally, the best way to view life extension opportunities is in multiples of current machine life expectancy. While, on the surface, multiples may seem optimistic, field studies have shown achievement of life extensions in excess of ten times.

In implementing a proactive contamination control program, three steps must be vigorously observed:

1. Set appropriate target cleanliness levels for each fluid system that will achieve machine life extension.
2. Upgrade or adjust filtration, breathers, etc., to achieve the cleanliness target with an adequate margin.
3. Implement an onboard or routine contaminant monitoring program serving as feedback to frequently confirm that targets are achieved and contaminant levels are stabilized.

Success depends greatly on setting appropriate life-extension targets (step one) and a maintenance discipline associated with active monitoring (step three). Surprisingly, fully implemented follow-up maintenance activities are relatively low in relation to pre-implementation levels, and depending on environmental ingestion rates, cost of filtration may not be adversely affected.

3.1 Cost-Benefit Analysis

Equipment maintenance costs can be broken down into three main areas: parts, labor and machine availability. These costs are a function of overhaul, repair and downtime. The accuracy of a cost-benefit analysis is limited by the completeness and accuracy of the records that contain these costs.

When dealing with mobile equipment, there are additional variables to be considered when evaluating maintenance costs. These have to do with the nature of field operation and field maintenance and repair. For example, a field mechanic may have to replace a part that is stocked 300 miles from an unscheduled breakdown. If availability is high priority, he may replace the part with a locally stocked item. This often causes inaccuracies in record keeping and/or a higher inventory cost.

The following is a short example of how a cost-benefit analysis can be applied:

XYZ Company has a fleet of 100 railway ballast regulators. The following steps are used to evaluate the feasibility of installing a condition-based maintenance monitoring program.

A. Current Machine Cleanliness

This parameter is the current hard particle contaminant level of the fluid system being evaluated.

The fluid cleanliness on the ballast regulator hydraulic systems is found to be an average of an ISO 19/16. The average engine cleanliness is found to be an ISO 20/17.

B. Machine Life Extension Factor and Required New Cleanliness

The calculation of these values is based on published studies (reference No. 4). The result is a determination of system life extension, based on the relationship between the previous contaminant level and a new lower contaminant level.

The Life Extension Factor for the ballast regulator hydraulic systems is determined from evaluation tables to be 3X if the Required New Cleanliness is an ISO 15/12. The Life Extension Factor for the engine systems is also determined to be 3X at a Required New Cleanliness of an ISO 16/13.

C. Filtration Cost Factor

The determination of the Filtration Cost Factor permits the calculation of the incremental cost of filtration associated with achieving the lower fluid system contaminant level.

The Filtration Cost Factors for the ballast regulator hydraulic systems and engines are found to be 3.5X and 2.5X, respectively, due primarily to high environmental particle ingestion.

D. Annual Overhaul/Repair Costs (Parts, Labor and Overhead)

Annual maintenance costs are tabulated as follows

a. Engines	\$75,000
b. Hydraulic Motors	17,500
c. Hydraulic Pumps	19,500
d. Hydraulic Cylinders	26,500
e. Servo Valves	8,500

XYZ repair records show that 65% of hydraulic cylinder damage and 15% of servo valve damage was due to breakage. Historical information has shown that 80% of wear related damage is due to contamination. The overhaul/repair figure adjustments are shown below.

Adjusted Annual Overhaul/Repair Costs (Parts, Labor and Overhead)

a. Engines	$\$75,000 \times 0.80$	= \$ 60,000
b. Hydraulic Motors	$17,500 \times 0.80$	= 14,000
c. Hydraulic Pumps	$19,500 \times 0.80$	= 15,600
d. Hydraulic Cylinders	$26,500 \times 0.35 \times 0.80$	= 7,420
e. Servo Valves	$8,500 \times 0.85 \times 0.80$	= 5,780

Total Adjusted Annual Overhaul/Repair Costs = \$102,800

E. Annual Associated Downtime Costs

This figure is based on the estimated downtime costs associated with the failures due to contamination.

XYZ Company found that \$265,000 in downtime costs were associated with the failures tabulated in the list of Adjusted Annual Overhaul/Repair Costs.

F. Other Associated Costs

This is the total of costs such as the costs to maintain spare part inventories, stand-by maintenance personnel and other overhead and maintenance costs that have not already been taken into consideration.

XYZ Co. found that spare part inventories and stand-by costs of maintenance on ballast regulators totaled \$35,000.

G. Total Annual Maintenance Costs

This is the total of D, E and F.

The Total Annual Maintenance Costs for XYZ Company is \$402,800.

H. Other Factors

Other factors used in the Cost-Benefit Analysis are Total and Previous Particle Counting and Sampling Costs and Annual Filter Change-Out Costs.

Once all the these factors are tabulated, the savings, Pay-Back period and Internal Rate of Return can be calculated.

In the case of XYZ Company, the condition-based maintenance program, with a total investment cost of \$192,600, would result in five-year savings of \$767,866, a payback period of nine months and an Internal Rate of Return of 68%. Benefits such as global positioning, production data management and other condition data was not included in this analysis.

3.2 The Application of Real-Time Contaminant Monitoring

The application of real-time contaminant monitoring, using on-line unattended sensors, has been successfully applied to railroad track maintenance equipment. The sensors receive a continuous sample stream from the hydraulic system and engine compartment. At frequent intervals, particle levels are assessed and transmitted to an on-board computer. The computer can be programmed to store and transmit the data at predetermined times of the day or work cycle. This can be accomplished by remote programming with satellite communication using the maintenance software. Alternatively, only exception levels are transmitted, i.e., contaminant levels and data trends that are above the target level.

The addition to the proactive "life extension" benefit of controlling and monitoring contamination in fluids, predictive maintenance benefits also exist. Since nearly all types of internal machine failures result in particle generation (through the process of wear and corrosion), abnormal particle contaminant levels may be the simplest test of impending machine failure. When real-time contaminant monitors are located upstream of system filters, the combined effects of contaminant ingestion, wear debris generation and filter performance can be assessed.

3.2.1 Real-Time Data Transfer

Real-time data can be defined as a constant stream of information stemming from its source. In our case, the source is a sensor or a monitor. Shown in figure 3.2 is the method used to transfer data from a gang of railroad work equipment to a single PC. This is one example of real-time data transfer with mobile equipment.

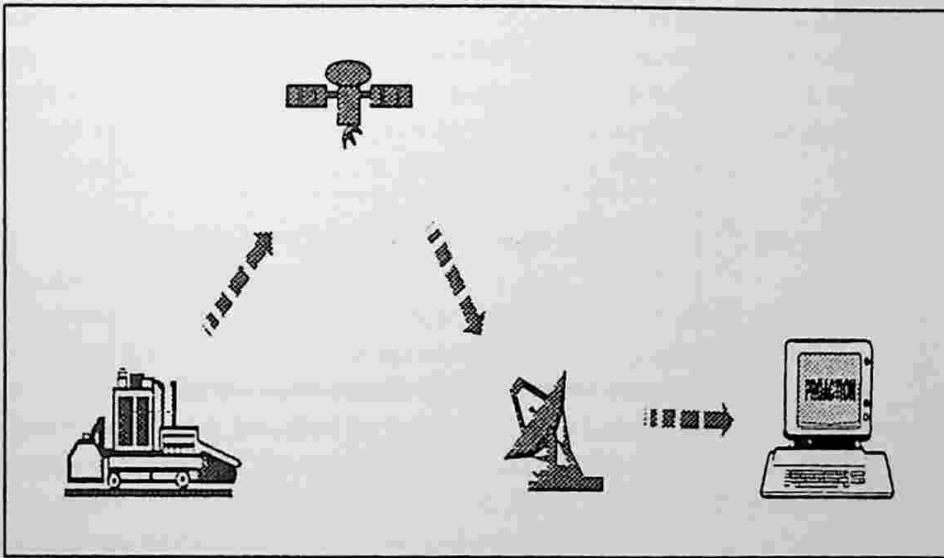


Figure 3.2

This method combines existing satellite technology with real-time condition monitors. As shown above, data that is produced by two condition monitors is stored in a data acquisition and control computer. This computer also controls the operation of the condition monitors and conditions the data produced. As frequently as desired, the data is reconfigured, stored, and sent in a single burst by a transceiver to a satellite. The satellite bounces the data down to a satellite receiving station (hub). This station reconfigures the code again and sends it by land lines to the end user's host computer. Once the code is received, the fluid condition diagnostic software interprets it, reconfigures it, reports it^a and stores it for future reference and trending.

3.2.2 Data Storage and Manipulation

Machine specific data received via satellite is stored for future reference. This is done so that the data can be called up at any time for graphing and trending. This may be useful in tracing the development of a failure or a simple equipment performance problem, or, as the data base grows, to perform in-depth studies concerning component life and reliability. All data received is stored for future use until it is erased by the end user. The illustration shown in figure 3.3 demonstrates the usefulness of this graphing capability.

^a see section 3.2.2 - Exception Reporting

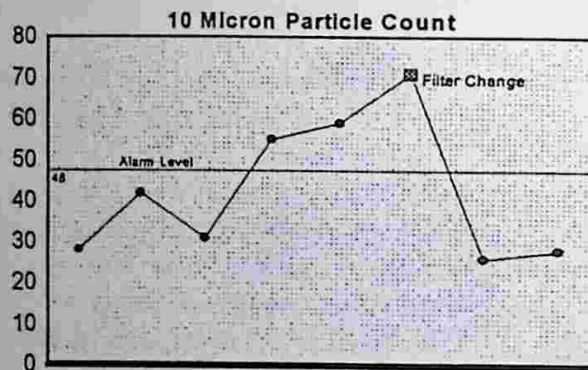


Figure 3.3

3.2.3 Exception Reporting

Since the amount of data required for real-time monitoring is high, it is better to let the software in the system sift through the data that is not immediately urgent. While this data is valuable information for trending, "stable" equipment conditions pose no immediate threat for the operators or managers. Therefore, exception reporting, which pulls only critical information from the incoming data, is a more efficient method of monitoring.

In the exception reporting used with the railroad equipment gang, the software alerts the user if adverse conditions exist within any of the hydraulic or engine lubrication systems. If no exceptionally poor conditions exist, no alarms are activated, and adequate machine health is assumed.

The fluid monitoring software program used divides fluid system conditions into five categories. These categories are referred to as "status levels." A status level "1" is good, a status "5" is hazardous, etc. Equipment operating at a status "1" do not trigger an exception report. However, any piece of equipment operating at a status "2" or higher is reported. The ISO contaminant level is listed on a screen and cannot be erased until a corrective action is reported on that particular machine. This action is typed into the computer and saved in the memory. Once this action is saved, the contaminant reading can be erased from the exception reporting screen. However, this data has already been stored in the data base for future viewing and trending.

The exception reporting system incorporates the use of function keys to trigger a listing of status dependent responses and possible actions. The possible actions given are based on the severity of the contaminant level in the system being monitored and are based on historical and technical information from similar equipment types. Once a specific system data base is enlarged, additional environmental and performance characteristics can be evaluated and additional suggested actions can be added to the system.

4.0 OTHER CONDITION AND SYSTEM MONITORING OPPORTUNITIES

Once a two-way satellite communications system is in place, many applications for its use become apparent. The integration of these applications should be cost/benefit driven. If the cost of any additional condition monitor is justified by a positive cost/benefit equation, it becomes a necessary expense. If the cost/benefit research for additional monitors and sensors is not completed or inconclusive, these additions may become, or may be viewed as, unneeded expensive gadgetry.

4.1 Moisture, Viscosity and Wear Debris Monitoring

The use of additional on-line sensors for monitoring other symptoms or root cause conditions can be more easily justified once the onboard computer and satellite communications equipment is in place. There are many options, and the use of sensors to monitor moisture, viscosity and ferrous debris are important to condition-based maintenance strategies. All of this of this real-time data can be linked to an expert system for on-board assessment of complex internal-state machine parameters.

4.2 Production Data, Temperature, Pressure and RPM

Many types of diagnostic information are easily and inexpensively monitored. The monitors used to obtain this data are normally found off-the-shelf and can be easily installed and integrated depending on priority and customer requirements. Data such as production information, that may be already transferred by other slower and more inefficient methods, can be transmitted quickly using satellite transmission, upgrading performance and asset utilization.

4.3 Messaging

If communication between manager and operator is important, text messaging systems can easily be installed. These systems are already prevalent in the trucking industry. The messaging systems not only provide a method of improving inspection capabilities and arrival time estimation, but also provide a communication link which can be used to alert operators of bad weather or of incipient problems if a contamination monitoring program is in use.

5.0 MAPPING CAPABILITIES AND REAL-TIME EQUIPMENT MANAGEMENT APPLICATIONS

The trucking industry provides a good example of the use of real-time equipment management, plus the application of constant position monitoring. The result has been significant improvements in "just in time" delivery performance. As with a fleet of trucks employing satellite transceivers, the railway work equipment referred to in this paper is constantly monitored for position using a software computer mapping system. This map can display individual pieces of mobile equipment as well as complete fleets. Movement histories show progression for a requested time period and also highly precise position coordinates.

This data enables the manager to attain high precision and efficiency in fleet scheduling and utilization. Because the position of the equipment can actually be seen, there is no longer a need to wait on word of mouth or telephone confirmation of position. There is also an elimination of doubt and/or miscommunication that may accompany a verbal confirmation of position.

6.0 SUMMARY

As we progress rapidly into the communication and information age, we are faced with a burgeoning need for continuous feedback of information from the systems that we operate and the projects we undertake. As this paper demonstrates, an efficient condition-based maintenance program is clearly needed on fluid-dependent systems, including mobile equipment. The challenge of integrating the use of unattended sensor technology on mobile equipment has been met by the application of high-tech satellite communications systems used in conjunction with modern condition-based maintenance software programs.

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