THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
Three Park Avenue, New York, N.Y. 10016-5990

99-GT-307



# REAL-TIME MONITORING OF BEARING CONDITION

**Barry Taylor**
GasTOPS Ltd.
Hoboken, New Jersey



## ABSTRACT

Magnetic chip detectors, vibration monitoring devices, and spectrographic oil analysis typically do not detect bearing distress until the bearing is in the latter stages of failure. Now, through the innovation of digital signal processing technology and a breakthrough in inductive sensors, it is possible to provide several months of advance notice on a bearing failure.

Unlike magnetic chip detectors, this technology has the capability to track the shedding of both magnetic and non-magnetic debris from the bearing. It is a true prognostic sensor that detects the first indications of a bearing spall and continues to track, in real-time, the quantities of wear debris being generated by the bearing. The data collected from the sensor can be changed into information such that with a particle trend graph it can clearly be seen when the bearing should be taken out of service prior to a turbine failure and the possibility of expensive secondary damage.

## INTRODUCTION

Bearing failures are one of the most costly and troublesome forms of unplanned outages for gas turbine operators. A failed bearing causes extended downtime and very high repair costs when secondary damage occurs in the engine. Preventing bearing failures has almost been a dream for power plant managers, until now. The following paper discusses the approach taken by Dynegy Power Corporation. Dynegy, a leading power producer with interests in 19 co-generation plants, 11 of which are located in California, has implemented a bearing failure-detection program at their Chalk Cliff Plant thanks to a new technology product. The results of this program have been extremely satisfying.

In the operation of a gas turbine, oil is critical to the survival of the machine. The lube oil is the engine's lifeblood, and just as blood tests are a key element of medical diagnosis, oil analysis plays a vital role in engine diagnosis. In theory, this is correct. In practice more efficient oil filters have reduced the effectiveness of spectrographic oil analysis as a diagnostic tool. More over, in today's competitive industry, a prognostic tool is required to predict when the turbine will require maintenance.

In the event that problems develop in the oil, then the possibility of a bearing failure looms. This can lead to secondary damage in the turbine, with a concomitant repair bill of more than $1,000,000. Traditionally, Spectrographic Oil Analysis (SOA) has been employed by gas turbine users to detect the presence of wear metals in oil. The consensus is that if a bearing is shedding particles, we will have a measurable concentration of material in the oil. SOA was designed to determine the concentration of elements, in parts per million, in suspension. It has always been a belief that SOA will provide an early warning of a potential lube oil related failure in a turbine. Does this work in reality? Look back over the years and recount how often an oil sample was taken. Can you remember just one instance where the diagnosis from a sample provided an advance warning of a bearing failure?

Today, there is a new technology that does provide prognostic information on bearing failures. The technology counts the debris in the scavenged oil flow as it returns to the sump from the bearing. MetalSCAN, with more than 300 units in the field, has had a number of successes as a prognostic sensor, often providing several months of advance warning. The sensor will detect both magnetic and non-magnetic wear debris in oil; this includes babbitt. Therefore, because it can distinguish between magnetic and non-magnetic material, it has the potential for use in various applications – internal combustion engines, gas turbines, steam turbines, gearboxes, and other critical machinery such as forced draft blowers. This article will discuss a recent incident on an LM5000, demonstrating the prognostic capability of the sensor. The results of this finding clearly show that this technology is superior to current diagnostic tools when it comes to predicting failures in a manner that will permit a planned outages as opposed to unplanned shutdowns.

## DISCUSSION

Oil system operations monitoring is now managed by the plant control system computers, with the occasional alarm to alert the operator to a problem. Oil condition monitoring is a laboratory process. Chip detectors and programs such as SOA have traditionally handled oil debris monitoring. This paper will focus on oil debris monitoring as it represents the best real-time approach to providing an advance warning of a bearing failure.

In looking at the technologies available to assist in the determination of problems associated with the operation of gas turbine plants, there are two main categories of tools - diagnostic tools and prognostic tools:

- ☐ **Diagnosis** – investigation or analysis of the cause of a condition, situation, or problem (diagnosis of engine problem).
- ☐ **Prognosis** – prediction of some future event or condition usually as a result of study and analysis of available pertinent data.

One tells you when you are now sick and have a bearing failure, the other predicts you will be sick in several months with a

Presented at the International Gas Turbine & Aeroengine Congress & Exhibition
Indianapolis, Indiana — June 7–June 10, 1999

bearing failure, or to put it another way, one forces an unplanned shutdown, the other permits a planned outage.

In the industry today most machines are insured against catastrophic damage, but they are not insured against minor damage, as the deductible would be prohibitive. One example of a problem that could cause either minor damage or major damage is a bearing failure. A bearing failure can either cause the gas turbine rotor to touch the stator, causing in excess of $1,000,000 in secondary damage, or it can be detected early and cause no damage to the turbine. In order to prevent catastrophic damage to the turbine, what is needed is a prognostic sensor, not a diagnostic sensor. A new technology bearing failure detection sensor called MetalSCAN can provide the required prognostic information. Recognizing this as a way to improve availability, Dynegy embarked on a project to install MetalSCAN in its Chalk Cliff facility.

### How Do Bearings Fail?

Clearly a bearing failure does not happen everyday. In fact, they are typically a 1/100 event according to one of the country's major insurance companies. If the machine is running in a heavy-duty application, then the loads on the bearings increase and so does the possibility of a failure. The statistics of a bearing failure do not seem to care whether the machine is new or old. In fact, the bearing refurbishment industry believes that a refurbished bearing has a better life expectancy that a new bearing because the infant mortality problem is not present in a used bearing.

Bearings fail for three major reasons, when you look at these reasons, you see the logic on failures:

- ❑ Dimensional Discrepancies. Dimensional discrepancies of rolling element bearings are the result of damage during or prior to service. Prior to the bearing being put into service, dimensional discrepancies can be introduced by flaws in the manufacturing process or they can be the result of improper handling or installation
- ❑ Overrolling of Debris. The over rolling of debris is a direct consequence of contaminated lubricating oil. The mechanism is straightforward; particles carried by the oil into the bearing are trapped between the rolling element and the race and are over rolled. If the material is hard, either the ball or the race or both will suffer an indentation. It sets up a localized high stress condition that will eventually cause a spall to occur.
- ❑ Corrosion Pitting. In this case chemical interaction occurs between the oil and the surface of the bearing, usually caused by reactive contaminants present in the oil. Such an interaction is frequently localized to a spot during periods of machine shutdown. The result is an imperfection in the mating surfaces of the bearing that initiates a fatigue process during operation.

## Diagnostic Approaches to Bearing Failures

There are a number of diagnostic tools available in the current inventory that can be used to detect a failing bearing in a gas turbine. These tools have been used for many decades, and there have been some improvements in their technologies, yet the tools themselves do not stand out as clear winners in the prognostic sense. They are clearly diagnostic tools that generally provide very linle advance warning of a failure.

- ❑ Vibration Monitoring. Vibration monitoring can occur either on-line in real-time, or on a periodic basis. Machines that are not mission critical, nor of high value, do not warrant the cost associated with having on-line vibration transducers; high value machinery does, as does mission critical machinery. Vibration monitoring works best when the sensor is located directly on top of the machine component that is creating the vibration. For example, a vibration pick-up located directly on top of a journal bearing will detect a change in vibration signature caused by bearing deterioration.
  - ➢ However, in the case of the aero-derivative gas turbine, it is not possible to mount the vibration pick-up directly on top of the bearing, they must be mounted on the casing. So the effectiveness of vibration in detecting a bearing failure in an aero-derivative gas turbine is small, at best. For this sensor to detect a bearing related problem, the damage has to be extreme. If the bearing damage is extreme, this means that the turbine should be shut down immediately, i.e. an unplanned outage.
- ❑ Magnetic Chip Detectors. Magnetic plugs are on-line devices that handle particles in the 50-1000 micron size range. The capture efficiency of chip detectors is less than 25%[1]. These units will false alarm with a small amount of debris, often called "fuzz", and just as often, they will not sound the alarm when a single large, 400-micron particle is trapped. Periodically, these plugs are removed and the debris is analyzed to make appropriate maintenance decisions. This is a manpower intensive process without a remote early warning indication of the problem. Given the poor capture efficiency, and the fact that the total mass of material that has been shed from the bearing cannot be accurately and rapidly computed, at best we have a diagnostic sensor.
- ❑ Electric Chip Detectors. While electric chip detectors may be applied effectively, a primary service problem exists. The amount of magnetic debris required to close the circuit can range from one large, well placed sliver up to 100 or more smaller sized particles, depending upon the nature of the debris population and the design of the chip detector. Furthermore, the contacts may be bridged with any size of debris, regardless of significance, making them prone to "nuisance" debris indications.[2] They are still diagnostic by design.
- ❑ SOA. SOA is an off-line process working in the less than 10-micron size range.[3] It is historically the only diagnostic tool capable of looking at both magnetic and non-magnetic debris in oil. However, filters have improved in capability and the effectiveness of SOA has declined as the filter traps most of the debris[4]. Furthermore, bearings shed particles in spurts, the roller when moving against the damaged part of the race causes particles to be released. When the roller is not in the damaged part of the race, no particles are released. Therefore, if SOA is to be effective, the sample should be taken when significant sized failure debris is travelling through the oil system. The question is "How does one know when to take the sample?".[5]

In today's world of power generation the cost of doing business is a critical issue, and the market place is driving plants to look for alternative solutions. The plant manager has many problems, and he is looking for health related solutions; diagnostic tools and prognostic tools are essential to the health of the company's bottom line.

## Prognostic Approach to Bearing Failures

The sensor, shown in Figure 1 is located in the oil line downstream of the bearings. It is a full flow sensor that will count particles in the oil flow that are larger than 125-microns.

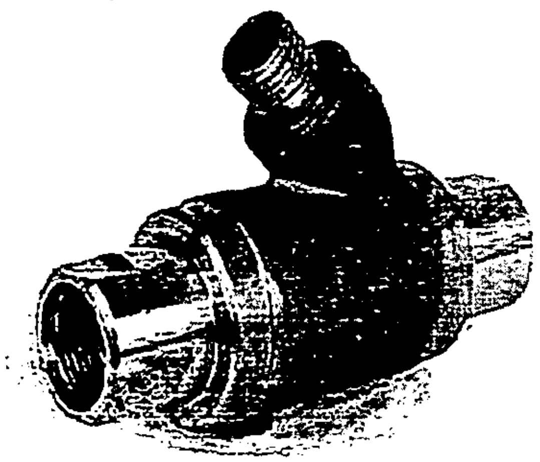

Figure 1 - MetalSCAN Sensor

MetalSCAN will detect a bearing failure from the point of the initial spall. This capability does not exist with vibration monitoring, SOA, and magnetic or electric chip detectors. Beginning from the initiation of the spall and tracking the bearing to failure, the sensor will count well in excess of 100,000 particles ranging in size from 125-micron to upwards of 700-micron as shown in Figure 2. The general characteristics of those curves have proven to be repeatable regardless of the size of the bearing. However, it should be noted large bearings will shed more particles before failure.

With the introduction of this technology into service, there have been a number of interesting facts that have recently come to light on how bearings fail. In MetalSCAN tests it was observed that:

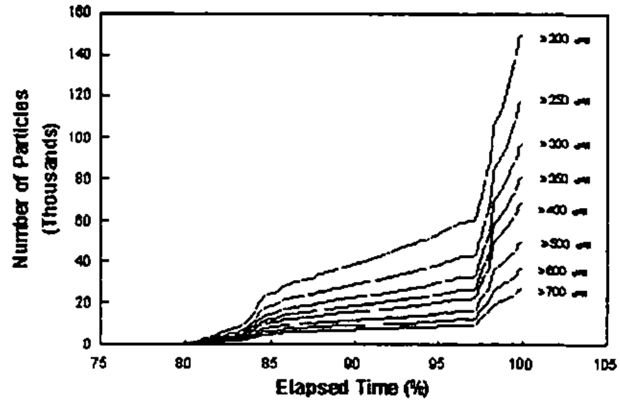


Figure 2 - Typical Particle Shedding Graph

- Bearings do not continuously shed particles, nor is the rate of shedding constant, they shed in spurts as indicated by the data in Figure 2. As the bearing gets closer to total failure, the rate of shedding increases dramatically.[6]
- The number of 100, 200, and 300-micron particles shed, is significantly larger than the number of larger particles (400 um plus).

### Chalk Cliff LM5000 Installation

The LM5000 in the Dynegy Chalk Cliff installation is outfitted with a MetalSCAN sensor on each bearing sump as shown in Figure 3. The sensors are located inside the gas turbine enclosure, and are connected to a control unit outside the enclosure. The controller will manage up to six sensors, and the controllers can be daisy-chained. The control unit is connected to a Personal

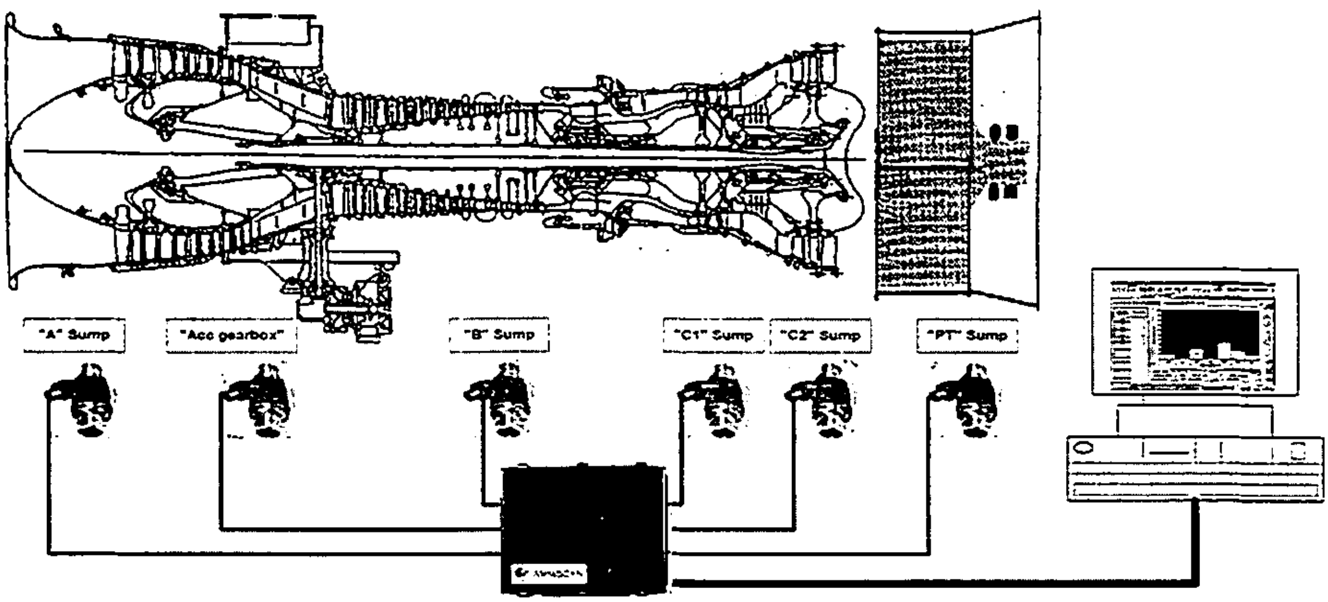


Figure 3 - Chalk Cliff MetalSCAN Installation

Computer in the control room using an RS-485 connection.

The sensor was calibrated at GasTOPS for the LM5000 and will not require any periodic calibration during its operational life. It should also be noted that the sensor does not require cleaning, or inspection, as is typical of other devices that measure wear debris from bearings. Figure 4 provides a good example of the length of the early warning time seen on the power turbine bearing in the Dynegy installation at Chalk Cliff.

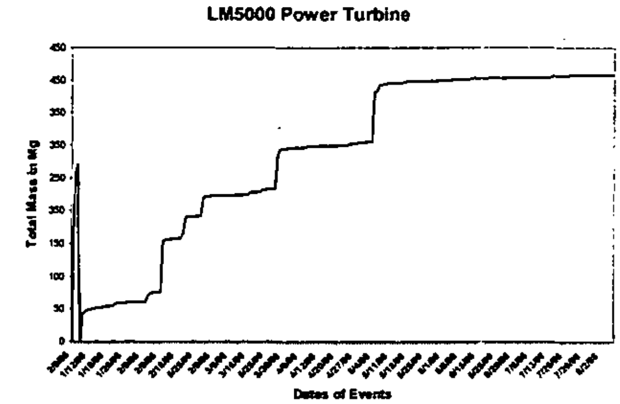


**Figure 4 - Bearing Failure Plot**

The Chalk Cliff LM5000 received a new power turbine on January 5, 1998. This power turbine had recently been repaired as a result of a bearing failure. As show in Figure 4, in the first three days MetalSCAN counted more than 5,000 particles (280 Mg of mass in total). This count fell off to near zero on day four indicating that the filter had cleaned the system of debris. These particles were attributed to a PT frame that was not cleaned well enough after the previous bearing failure. On day four, the software was reset to zero to normalize the results to a baseline of experience. Since then the sensor has been counting particles on an intermittent basis.

In mid-February, the oil temperature jumped 20°. This normally would have caused an immediate shutdown with a concomitant loss of revenue. Instead, it was decided to provide the grid with seven days notice, so that no financial penalties would be incurred. When the machine was shutdown a week later, the following significant points were noted:

- ❑ MetalSCAN has counted more than 4,000 particles – a total of 180 Mg of mass.
- ❑ The sump RTD had partially failed.
- ❑ One of the PT magnetic chip detectors had trapped two small 1/8th inch slivers.
- ❑ Vibration monitoring showed nothing abnormal.
- ❑ SOA showed nothing abnormal.
- ❑ The oil filter contained thousands of particles.

The machine was put back on-line and continues to operate as the alarm line for this bearing is set at 2,000 Mg of mass.

Investigation into this turbine shows that the machine currently sheds the majority of its particles roughly five minutes after a start. This would indicate that the power turbine bearing has either a misalignment or differential expansion problem that is corrected after the turbine reaches temperature and speed. The current total particle count is in excess of 10,000 particles and climbing. It should be noted that the sensor, installed in the PT scavenge line on an LM5000, will nominally count more than 100,000 particles before the bearing hits the warning line, thus there is no opportunity for a false alarm from fuzz as can occur with chip detectors. Since the sensor counts large volumes of particles, there is no opportunity to miss the warning normally associated with devices that look for a few particles. With an alarm line of 2,000 Mg, a planned outage should occur later this year.

## Bearing Failure Warning Line

As shown in Figure 2, the rate that particles are shed from the bearing toward the end of the failure increases dramatically. This works to MetalSCAN's advantage and can be used to set the warning line, as the data has been consistent over a large number of bearing failures.

The race on a rolling element bearing tends to be the weak point as shown by the example in Figure 5. It would appear from the bearing test program that when the damaged part of the race is large enough to permit two rollers to remove metal, the rate of spalling increases dramatically. The best parameter for indicating severity of steel bearing damage is the total accumulated ferromagnetic mass. Using the pitch diameter and the diameter of the rolling element, it is possible to define the warning and alarm lines for MetalSCAN. In other words, if we know how big the bearing is, the type of bearing, and the roller size, then we can set the amount of mass we would expect to see removed from the bearing before it enters into a dangerous situation

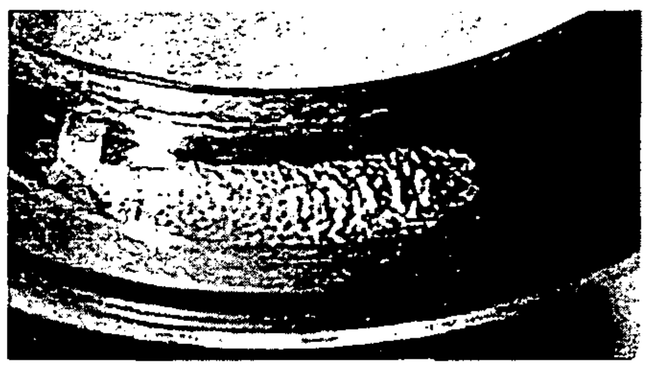

**Figure 5 - Damaged Race**

Although not shown in Figure 4, the alarm line has been set at 2,000 Mg for the 18-inch rolling element bearing on the Chalk Cliff power turbine. The bearing has been operating for 8 months, shedding particles with a total removed mass of about 400-Mg. It is clear from this data, that the plant manager has sufficient time to plan an outage to fix the problem. In this case, the problem turned out to be a misaligned PT bearing. Once the alignment was corrected, the particle shedding rate slowed dramatically, but the bearing continues to shed particles in very small numbers.

**Insurance & Bearing Failure Costs**

According to a major insurance company source, bearing failures in gas turbines occur at the rate of about one in one hundred. That is to say, if 100 machines are running this year, then one of these machines will have a bearing failure that causes major secondary damage. The insurance companies do not provide insurance for failures that result in insignificant damage. In the stationary turbine world today, there are more than 15,000 gas turbines operating in the electrical generation or pipeline role. Therefore, statistically, 150 bearing failures could occur this year.

This particular gas turbine example is an LM5000 being used in the electrical generation role as the prime mover in a co-generation plant. The machine is insured against loss of revenue and catastrophic damage. The insurance deductibles are of the order of $250K for loss of revenue, and $500K for the damage policy. These deductibles change based upon plant performance, just as car insurance premiums change based upon the number of accidents. Therefore, for each major incident of severe turbine damage the cost to the owners will be the deductibles - $750K.

Insurance does not cover minor breakdowns, and it is not practical to make an insurance claim unless the damage is going to be in excess of the deductible. For example, if the turbine comes off-line without notice because of a sensor failure, based upon the contract with the host or the grid, some co-generation companies can incur an immediate $8,000 penalty. If they are down for a substantial period, this penalty can peak to $25,000. Again, insurance does not cover these nuisance shutdowns.

In a bearing failure on an aero-derivative machine, there can be many costs incurred. The most expensive costs are associated with the unplanned outage, and the least expensive are related to a planned outage that does not cause secondary damage. This information is shown in more detail for the following three cases:

- **Case 1 - Cost $750K**. The bearing fails and there is no warning from the vibration transducers, the chip detectors, or the SOA. The operator sees the oil temperature rise 20° and shuts the machine down as the rotor and stator touch to trigger the vibration alarm. This machine has to be removed for a major overhaul. The total cost for this type of an event is $1.8M. This includes the cost of repairing the machine, the leased turbine, the Field Service Engineer, and the plant staff on overtime. The insurance company is called, and the cost to the plant is the $750K deductible. Next year the insurance premiums will rise.
- **Case 2 - Cost $408K**. The bearing fails causing no secondary damage because the operator shut the machine down before the rotor touched the stator. In this case, the costs are about $120K for the repair and the leased machine. This is all done on overtime with a lease machine immediately available. The lost revenue at $2,400 per hour for 5 days = $288K.. The damage and the lost revenue costs are not great enough for an insurance claim, so the plant absorbs the costs.
- **Case 3 - Cost $55K**. The bearing is predicted to fail two months in advance. The plant manager places an order for a spare bearing and field service support. The bearing is to be replaced during a planned outage, not an unplanned shutdown. In this case, there is no lost revenue as this was a planned outage. The cost to change the bearing is $55K.

Clearly a bearing failure does not happen everyday. In fact, they are typically a 1/100-event according to a major insurance company. If the turbine is running hard, then the loads on the bearings increase and so does the possibility of a failure. Statistically, there is a good chance of a machine having a bearing failure. The question is, will it be an inexpensive or an expensive failure? Given the choice of a planned outage, vs. an unplanned shutdown, the first is preferred. With a prognostic sensor it is possible to change the damaged bearing in a planned outage.

## CONCLUSION

Clearly a prognostic sensor that can detect the first spall of a bearing and track the debris being shed from the bearing is the preferred approach. Based upon the size and type of bearing, MetalSCAN provides the operator with a warning on when to shutdown a turbine that is suffering a bearing failure. Catastrophic damage can result in damage to the shaft and to the stationary sump components. This technology removes the fear of catastrophic secondary damage to the turbine and at the same time ensures that bearing failures can be handled at planned outages, not unplanned shutdowns.

It is clear from the installation of the Chalk Cliff power turbine that there was a large influx of particles upon start-up. Given that the other engine sumps did not exhibit the same characteristics, it was concluded that the PT frame was not cleaned well enough after the previous bearing failure. The LM5000 at Chalk Cliff had been operating for more than eight months with the power turbine bearing shedding material. After realignment, the power turbine bearing continues to shed very small amounts of material. MetalSCAN is actively monitoring the quantity and size of the debris that is being shed by the bearing, and is set to provide the operator with a conservative warning when the total mass exceeds 2,000 Mg. The key advantages of this new technology are:

- The length of the early warning time provided to allow a plant manager to plan an outage well into the future.
- The ability to track the progress of the bearing distress.

## REFERENCES


1 Higgins P.D., Crowe J.T., "Advances in Commercial Engine Lube Debris Monitoring", Pg. 2, SAE paper 972603 Aug. 1997.

2 Crowe J.T., Higgins P.D., "Lube Debris Monitoring Marches On", Page 51. Aircraft Technology Engineering & Maintenance Engine yearbook 1997-98.

3 Tauber, Thomas, SAE Paper 831477, "A Guide to Gas Turbine Engine Oil System Monitoring", October 1983

4 Whitlock, R.R., Humphrey, G.R., Churchill, D.B., "The Path to Affordable Long Term Failure Warning: The XRF-Wear Monitor", 1998 Technology Showcase, JOAP International Condition Monitoring Conference, Pg. 250, Apr. 1998

5 Higgins D., and Johnson R., "Real Time Quantitative Lube Oil Debris Monitoring for LM Engines", Western Energy Magazine, Fall 1996.

6 Muir D., and Howe B., "In-Line Oil Debris Monitor", Aerospace Engineering Magazine, October 1996.