# Condition Monitoring Applied to Industrial Machinery

## *How Condition Monitoring Programs Contribute to the Bottom Line*

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### INTRODUCTION

Condition monitoring tools and technologies are widely utilized in industry today. Structured *predictive maintenance p*rograms are implemented with the objective of implementing condition based maintenance. Other maintenance approaches, either run-to-breakdown or preventive (time-based), are generally more expensive for industrial machinery. Condition monitoring can reduce maintenance costs, increase reliability and increase availability. Properly executed, there can be substantial economic benefit from such programs versus preventive or breakdown maintenance.

This presentation provides an overview of existing, proven condition monitoring methods, with some examples and illustrations. Limitations are indicated. Aligning the technical programs more directly with company financial objectives is discussed.

### THE PROFIT CENTRE VIEW

To more clearly understand the role of condition monitoring, let us start by considering a machine as a profit center. This exercise is important since the purpose of starting and operating production machinery is to make *as much money as possible.*

*Profit = Revenue - Cost*

Revenue is simply the throughput or units of production multiplied by the value added to each unit produced. The amount of production from a machine will be the production rate (e.g. units per hour) times the number of hours run in the time period. The number of hours run is the total number of hours in the period times the availability, assuming a continuous operation.

On the expense side, we will consider only the variable costs that we have a chance to control: maintenance, energy and operating costs. Cost of capital (or depreciation) is not really a variable for our purposes. The profit equation becomes:

*Profit = (availability x hours x production rate x unit value added) - energy costs - operating costs - maintenance costs*

A better way of looking at the profit equation:

*Profit = availability x hours x production rate x { unit value added - (unit energy costs + unit operating costs + unit maintenance costs ) }*

"Unit" energy, operating and maintenance costs are defined as meaning the cost per unit of production, such as energy cost per unit volume of gas compressed or per ton of pulp produced or per widget manufactured.

The key variables are:

- availability
- throughput rate (capacity utilization)
- unit energy costs (efficiency)
- unit maintenance costs
- other operating costs (oil, filters, …) per unit of production

From these considerations, we can see that:
- availability is more important than reliability; that is, we want to minimize the total of planned and unplanned down time, not just the unplanned.
- rather than minimizing maintenance costs, our objective should be to minimize maintenance cost per unit of production; we should do the minimum amount of maintenance required to get the maximum units of production
- pursuit of reduced unit energy costs (improved efficiency) is valid
- we should pursue a throughput rate (load level) which is the maximum sustainable without causing disproportionate increases in maintenance costs or decreases in availability

**THE ROLE OF CONDITION MONITORING**

Condition monitoring tools and programs are essential if we are to achieve the best economic results. The table below indicates the linkage between condition monitoring activities and the key factors in the profit equation. Note that there are many opportunities to measure machinery attributes in economic terms, such as the cost of deviation in performance or efficiency. An actual example will be shown.

| Profit Factor | What can condition monitoring do? |
|---|---|
| throughput rate (capacity) | Measure throughput; detect deviation from normal; identify opportunity for improvement; determine cost of deviation |
| availability | Enable maintenance to minimize total planned plus unplanned down time; measure availability; identify operational abuse |
| maintenance cost<br>Per Unit Of Production | Provide basis and information for doing just the right amount of maintenance, just-in-time |
| energy cost<br>Per Unit Of Production | Measure energy consumption; measure efficiency; determine deviation from baseline; measure cost of deviation; identify opportunities for improving baseline |
| operating costs<br>Per Unit Of Production | Measure energy consumption; measure efficiency; determine deviation from baseline; measure cost of deviation; identify opportunities for improving baseline |

If we can maximize the economic performance of each machine, we will have a positive impact on the overall corporate results.

## MACHINERY ATTRIBUTES WE NEED TO MEASURE

Profit considerations tell us we need to measure and optimize:

- throughput and capacity utilization
- performance including outputs, inputs, efficiencies and waste
- mechanical condition and risk of failure
- economic consequences of deviations in mechanical condition and performance

Measuring and evaluating performance and capacity utilization is generally reasonably straightforward, though not trivial. For gas compression machinery with varying operating conditions, identifying deviations in performance or efficiency requires normalizing measured performance data and comparison with baselines - preferably test-based baselines.

The more difficult area is that of mechanical condition. The measures are necessarily less objective. When we see an indication of a fault, everyone wants to know how much longer the machine can be run. It is impossible to know with precision. (However, monitoring for rate of change is a big help in making decisions.)

The need to minimize maintenance cost per unit of production implies minimizing maintenance resources consumed, but this must be balanced against ensuring throughput, efficiency and availability. So the challenge is applying just the right amount of maintenance at just the right time. Condition monitoring can help develop the maintenance program to achieve this end and can help manage individual incidents to the same end.

## MACHINERY MONITORING PROGRAMS

This section will present an overview of the most common condition monitoring programs for industrial machinery:

- lube oil analysis
- vibration spectrum analysis
- reciprocating engine/compressor analysis
- analysis of operating parameters
- ultrasonics
- thermography

These programs are generally complementary, not overlapping. Monitoring all aspects of condition and performance often requires all of the above.

### Lube oil analysis

Analysis of lubricating oils has three main aspects:

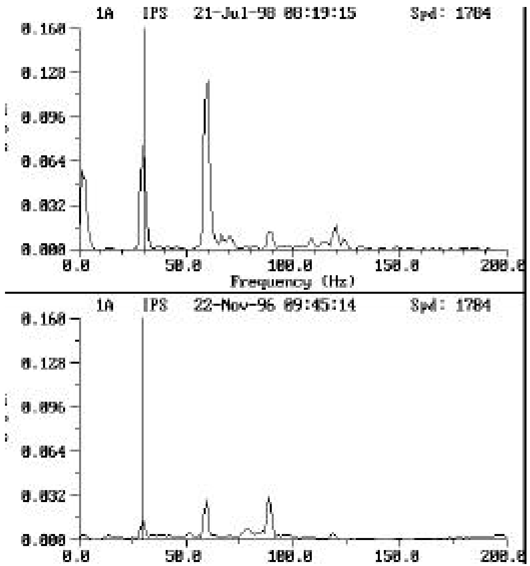
1. Detection of abnormal concentrations of wear particles, usually metals, which would indicate accelerated wear of the machine.
2. Analysis of the physical and chemical properties of the lubricant to ensure that it can perform its job and determining any corrections required. This contributes to prolonged machine life.
3. Detection of contaminants such as dirt and glycol which contribute to accelerated wear and can also indicate problems such as a leak.

Lube oil analysis is carried out most commonly by periodic sampling and laboratory analysis. Some field analysis may be practical and economic; e.g. hard particle concentration, moisture levels and viscosity. Information from oil sample analysis can be used to contribute to condition based maintenance, to prolong machine life and to reduce lubricant costs.

Practical difficulties and limitations include: difficulty in getting reliably representative samples; time delay when using outside laboratories; difficulty in verifying anomalous results.

### Vibration spectrum analysis

Vibration-based predictive maintenance is based on the fact that in rotating machines, many machine faults create increased vibration levels. Monitoring overall or band-filtered vibration level provides an alert mechanism for machinery protection. For condition monitoring and diagnostic purposes, more detailed analysis of vibration signals is required.

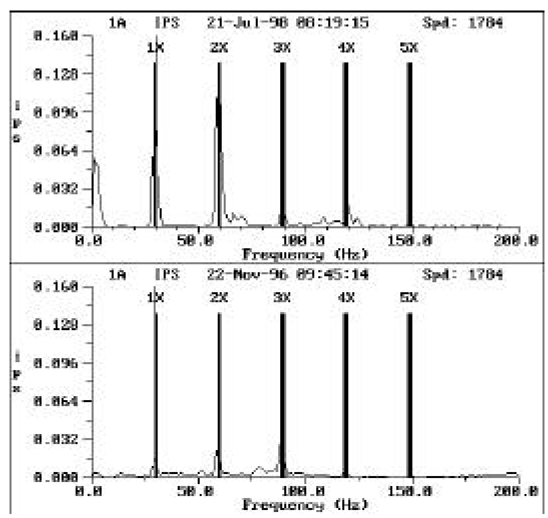



Predictive maintenance programs generally involve analysis of vibration spectra, such as the example to the left. The distinct peaks in the vibration patterns at certain frequencies are due to machine behaviour; the challenge is to determine whether the behaviour is problematic. Notice in this case that there has been a large increase in some components compared to the 22-Nov-96 baseline.

Vibration-based predictive maintenance is widely applied to rotating equipment. Benefits realized include extended machinery life, reduced catastrophic failures and secondary damage, and increased availability.

Practical problems/limitations:

- making valid decisions is as much art as science
- periodic type programs are (skilled) manpower intensive
- continuous diagnostic systems are expensive to implement and not always reliable
- some faults do not affect vibration significantly

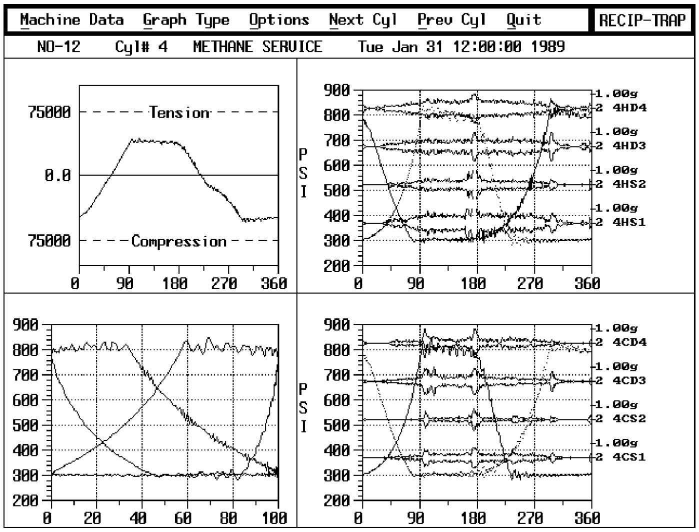



Some software tools are available to help the user identify the characteristic “fault” frequencies in the spectrum. In this case, we see that the peaks at 1X and 2X (running speed and twice running speed) have increased compared to their 22-Nov-96 baseline amplitudes. This is an axial vibration measurement as denoted by the testpoint label “1A”. The symptoms are typical of misalignment.

### Reciprocating engine/compressor analysis

Condition analysis of reciprocating compressors and engines requires a different approach. Because of the normal vibration of these machines, vibration spectrum analysis is of limited value. Instead, vibration is filtered to remove the low frequency shaking components. The remaining signal, possibly with further filtering, is analyzed as a function of crankshaft angle. Where in-cylinder pressure can be measured, it is also captured with respect to crankshaft angle.

The above data is supplemented by some basic operating data, such as gas temperatures and running speed. Spectrum analysis can be beneficially applied to rotating accessories like turbochargers. Using a modern engine/compressor analyzer, a skilled analyst can identify a wide range of incipient failures and performance anomalies.

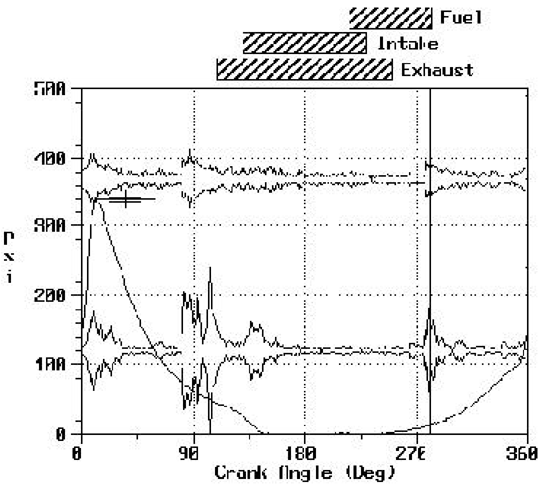



This illustration shows reciprocating compressor data from an engine analyzer. The upper right shows a pressure-time curve for the head end (solid curve), with filtered vibration traces from each valve cap overlaid. The crank end pressure-time curve is shown dotted for reference. The lower right is the same picture for the crank end.

At the lower left, pressure-volume curves for both head and crank ends are shown. An experienced analyst would recognize that this head end curve is abnormal, and also that the head end valve cap filtered vibration patterns are not what we would expect. The problem is a leaking discharge valve - specifically, the valve labelled 4HD4.

At the upper left is a rod load plot calculated from head and crank end pressures.

This data can reveal problems such as: leaking valves, leaking rings, excessive HP losses, rod overload, lack of sufficient rod load reversal, crosshead looseness, poor valve dynamics. Some application software is available to assist with detection of problems and to provide some economic measures, such as the excess cost caused by a leak.



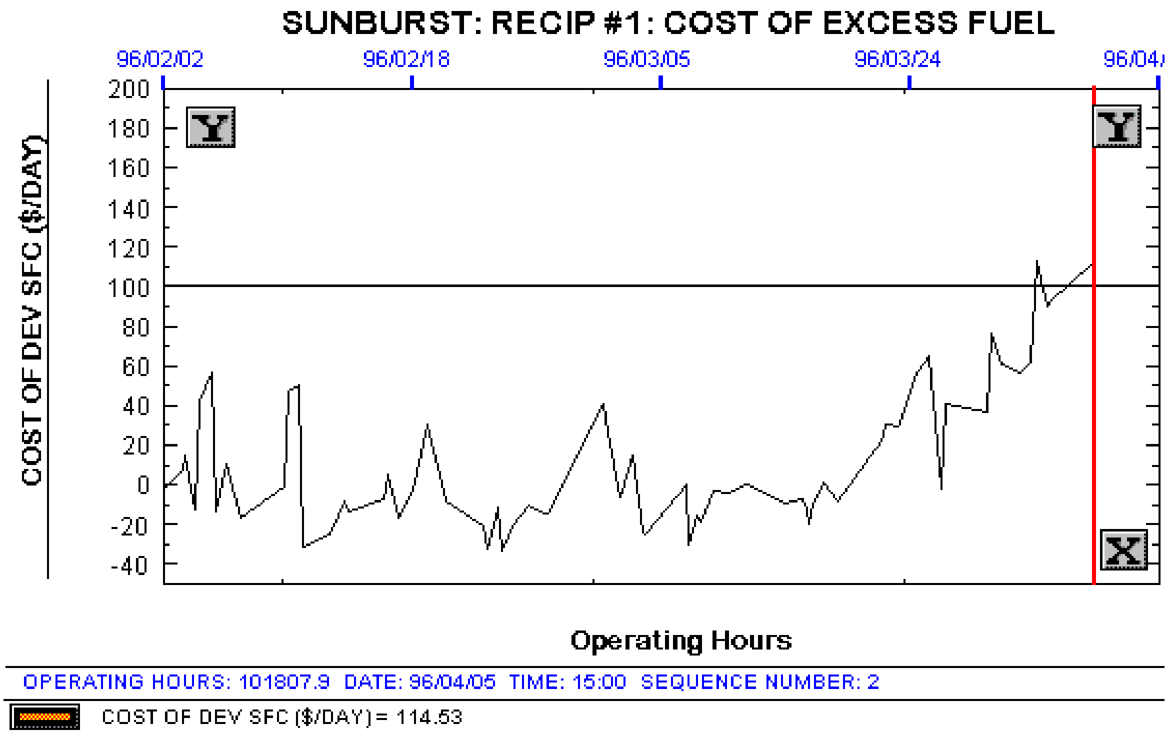

Power cylinder condition and performance can be evaluated from filtered vibration readings and in-cylinder pressure versus crankshaft angle. High speed engines (900 RPM and up) generally do not have provision for measuring firing pressures, so vibration patterns are used to evaluate mechanical condition. In the example at the left there is a pressure-time curve, a filtered vibration pattern (lower) and an ultrasonics pattern (upper).

Analysis of this type of data can reveal: ring blowby, leaking power valves, worn/scored liners, excessive wrist pin clearance, valve train looseness, worn guides, incorrect valve timing, poor combustion. Operating parameters also should be included in the analysis: air manifold pressures, air manifold temperatures, ignition timing, fuel flow rate or pressure. Measuring crankcase blowby through a venturii meter is worthwhile.

**Analysis of operating parameters**

A large amount of operational data is already being collected in most facilities; typically on log sheets or by a control system. This process is not generally regarded as part of a condition monitoring or predictive maintenance program. However, there is usually a lot of valuable machinery performance and condition information buried in this operational data. In practice, the challenge is filtering out the useful information.

What data is useful is very machine and application dependent. For example, for a reciprocating compressor in a very stable service, we could closely watch for any increase in discharge temperature to detect internal leaks; ring or valve. But the same machine in a pipeline application with widely varying operating conditions would require that we normalize the discharge temperature. Operational data often is adequate to allow for calculations of efficiency and detection of deviations in efficiency, which can then be extended to calculate the cost of such deviations. On a gas turbine driver, this type of monitoring and analysis can be used to determine when it is most cost effective to perform blade washes.




This example illustrates how basic operational data can be turned into useful information for making economically driven decisions. The figure shows the trend of something called “cost of deviation in specific fuel consumption”. In other words, this is a measure of the cost of wasted fuel for this engine. Any deviation above zero is, theoretically, an excess cost.

To get to this point we start with measured gross fuel flow rate; e.g. cubic feet per hour. We also need an estimate of engine BHP; we can usually get this from operational parameters on the driven machine. The next step is to calculate the current BSFC (brake specific fuel consumption), which is the equivalent of determining thermal efficiency. Then the current BSFC is compared with the baseline or expected value; zero in this case. When the current value is greater than the baseline, all or part of the excess is viewed as recoverable and is used to calculate a cost for excess fuel consumption.

In this case we see a significant rise in this cost to the point that it exceeds an alarm (indicated by the solid line) of $100 per day. Not only does this tell us that there is a performance problem with this machine, but it also puts the problem into economic perspective. Measures of this sort can greatly assist with prioritzing maintenance decisions.

### Ultrasonics

Here we refer to ultrasonics applied to condition monitoring of machinery. Other applications, such as evaluating corrosion in piping, are also worthwhile.
For rotating and reciprocating machinery, ultrasonics is a specialized measurement used to detect energy from mechanical impacts or high velocity gas flow. Generally, ultrasonics measurements look for acoustical or mechanical energy above about 20k Hz. There are a number of fault conditions that will produce energy above this frequency:

- leaking valves in reciprocating compressors
- worn gears or gears with improper mesh
- improper lubrication
- rolling element bearing faults

Ultrasonics is more a sensing technology than a condition monitoring program. It is usually used along with other sensing and analysis techniques to form a more comprehensive program.

### Thermography

Measurement of temperature can detect some machinery abnormalities. Such measurements are usually carried out with non-contacting, infra-red technology. One approach is to use an infra-red camera, though this equipment is more commonly applied to non-machinery applications; e.g. electrical switch gear. A second approach is to use an infra-red temperature transducer which gives a temperature readout for a point or small area.

Temperature surveys can be used to detect abnormalities in components such as rolling element bearings, compressor valves, electric motors, engine fuel valves; basically any situation in which a developing fault will result in a significantly increased temperature at some accessible surface. Infra-red temperature measurement is a significant supporting technology but is not by itself an adequate condition monitoring program for machinery.

## TURNING DATA INTO INFORMATION (THE DRIP PROBLEM):

Successful application of condition monitoring requires overcoming obstacles including:

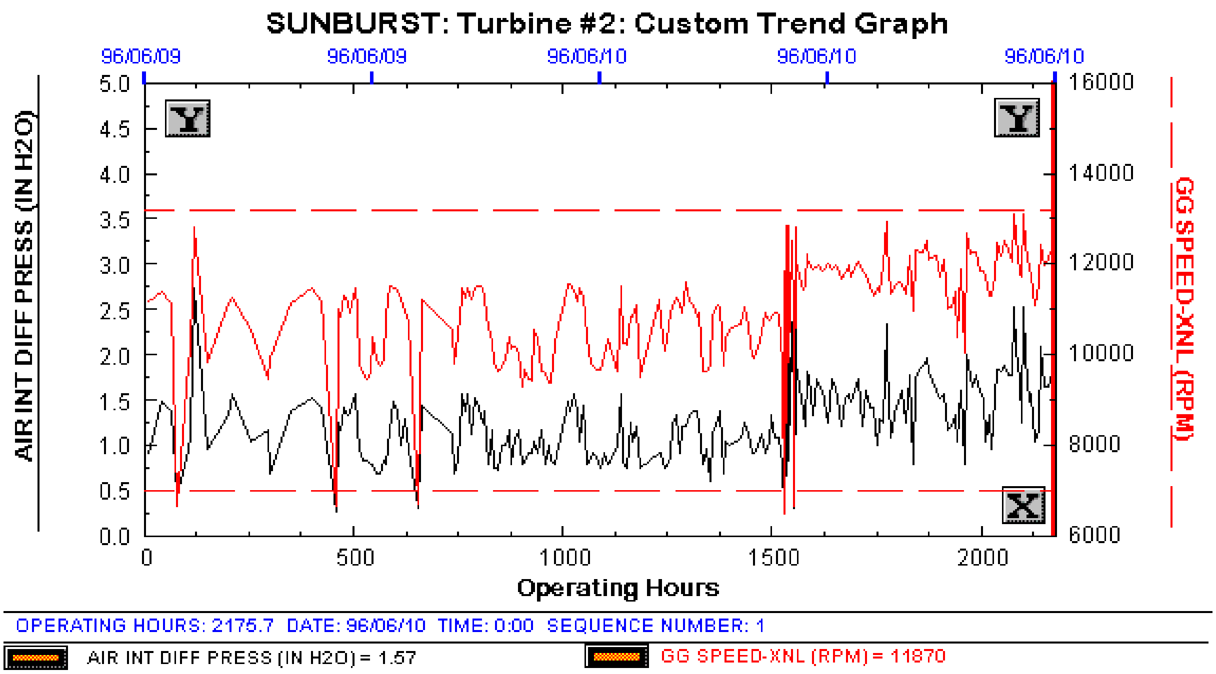
- a large amount of data
- transforming data into information; overcoming DRIP (data rich/information poor)
- a comprehensive program is made up of several technologies or sub-programs; each existing in isolation from the others; result: islands of information
- typical condition monitoring programs have no explicit economic thrust

To turn data into information:
1) We must process the raw data in order to extract needed characteristics or measures
2) It is essential to reduce the large volume of raw data to a few key measures
3) It is important to automate the process as much as possible

Some methods of data analysis:

- filters or extractions; e.g. amplitude at 1X in vibration spectrum
- models; e.g. efficiency calculations
- statistics; e.g. peak firing pressure average and standard deviation
- ratios; especially current level to baseline level
- spread ratio; high minus low divided by average; e.g. gas turbine temps
- deviation from some reference:
  - a baseline determined with the machine in as-new condition, perhaps involving a carefully executed test program.
  - theoretical value or level
  - benchmark; compare with the same measure from other, comparable machines or machine components

Some examples:
>> vibration energy compared to baseline; either overall or spectral components
>> efficiency; deviation from baseline
>> discharge temperature delta for reciprocating compressors

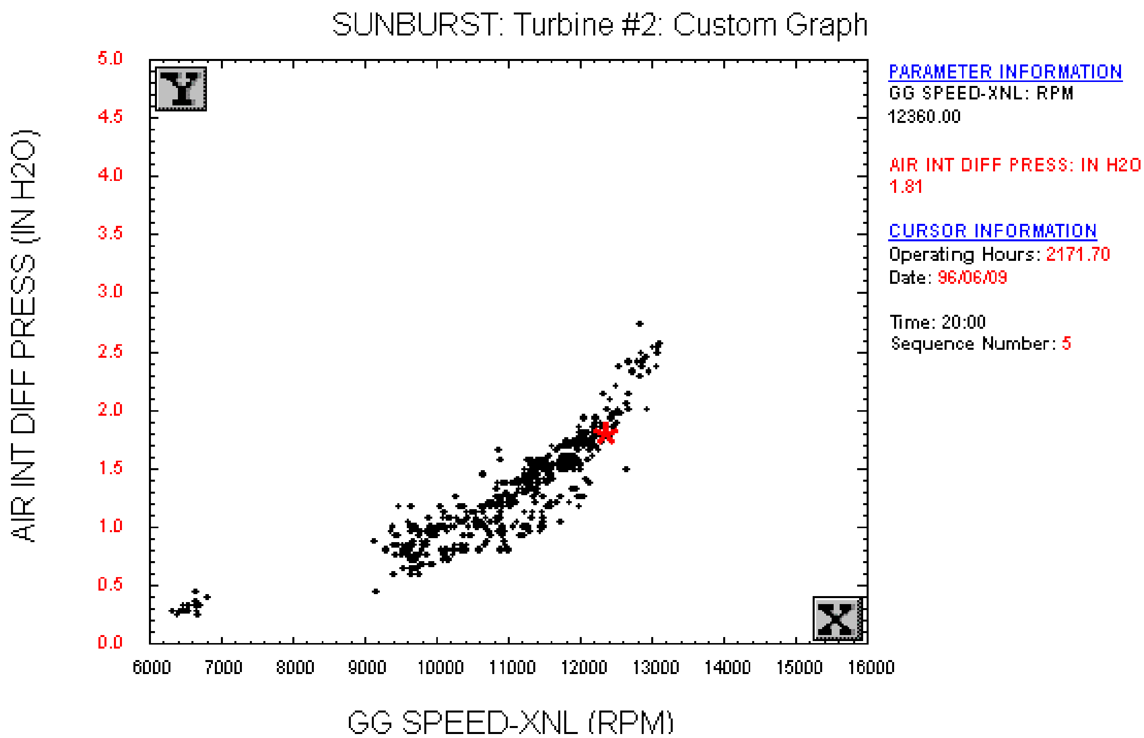



This is an example of extracting a feature of interest from raw data. In this case we are interested in the pressure drop across the air inlet filter in a gas turbine. Increased pressure drop due to accumulation of dirt or to ice formation will decrease unit efficiency and performance.
The lower curve in the trend graph shows air inlet pressure drop, in inches of water, over about 2000 operating hours. We see that there is a noticeable increase after 1500 hours. From this curve alone we cannot determine whether the increase is due to deteriorating filter performance or due to changing operating conditions. If the unit is loaded more heavily, then it must move more air, so pressure drop can increase for that reason.

The upper curve is the gas generator speed, which will basically determine air flow rate. We can clearly see how the two variables move together, so we can conclude that the filter itself has not deteriorated. However, this visual check could easily fail to identify subtle changes in filter performance that an improved measure would readily reveal. In addition, automatic alarming would not work well unless we normalize the measure.

One way to do this is shown below. Measured differential pressure data points are plotted against gas generator speed (proportional to air flow) in an x-y graph. Clearly there is a very strong correlation. Then what we should do is create a baseline relationship between gas generator speed and air intake differential pressure with all components in normal condition. This can be accomplished by fitting a curve to some or all of the measured data points.

In the condition monitoring program we would then add a new parameter that we might call “deviation in air intake differential pressure” which measures how far the current value falls from this baseline.




Note that there is potential to go a step further. We should be able to estimate from existing data the amount of efficiency loss for a given increase in intake pressure drop. This would enable the calculation of extra fuel cost, thereby supporting an economically driven decision on filter cleaning/replacement.

**SUMMARY AND CONCLUSIONS:**

Properly applied and selectively applied, the condition monitoring programs that have been described here can return benefits well beyond the cost of the programs. There is a substantial amount of experience and judgement involved; the programs are not automatic, nor are they “pure science”.

Experienced specialists should be involved in the design, implementation and execution of condition monitoring programs.