Continuous Stress Wave Monitoring For Failure Progression Analysis

CONDITION BASED MONITORING SOLUTIONS

ABSTRACT

Failure of a bearing or other mechanical component within any machine is usually a process that occurs over a time span ranging from days to weeks to even months. Unfortunately, users often don't become aware of the failure process until it has progressed to the point of generating metal particles in the lubricant, producing abnormal vibrations, or even creating a temperature rise in the machine. By that point the machine is entering its latter phase of the overall failure process, and it may be too late for inexpensive remediation. Once this degradation has occurred, the ability to closely monitor the failure progression, and even make operational changes to 'nurse' the machine to the next less-inconvenient outage time, may be the best or even only available strategy to mitigate cost while sustaining the remaining machine health.

Friction is the first indicator of many problems, and a precursor to secondary problem effects such as vibration, material loss, and temperature increases – changes in friction can indicate problems with lubrication and other factors well before any physical damage results. Beyond problem prevention, friction levels can also be correlated with operational speed/load to identify the operating levels that are optimal for asset lifespan. Based on measuring actual friction, StressWave monitoring and analysis provides a much earlier identification of degradation in the failure process, as well as the ability to monitor the failure progression and optimize machine performance and maintenance. This paper will explain the basis of StressWave analysis, as well as discuss the various analytical approaches that can be taken with stress wave data for machine condition determination.

INTRODUCTION

Machine failure is not an event; it is a continuous process with distinct stages that resulting from friction. The cost and effort required for repairs and remediation of this process increases as the damage progresses into latter stages. All machines have some level of friction at the points where moving parts contact with stationary parts, or where parts are moving at a different speeds – usually such contact points are lubricated, even if the lubricant is air. Friction is always present when a machine is running under steady-state conditions, and friction events will occur when loading changes take place. But this typical friction causes machine wear, causing surfaces to break down and release material over time. As friction increases, there is usually a temperature rise, even if it is only localized, which accelerates the material break down. These defects then expand and spread until the whole machine will eventually begin to exhibit abnormal vibration and localized temperature increases – this cycle repeats until damage or wear is sufficient to require repairs. Figure 1 gives a simplistic overview of this concept.

In many instances, the first phase of machine deterioration occurs as a result of lubrication or alignment problems, or even machine set-up errors. These problems may be too minor to detect on most monitoring systems, but they will start the machine down the failure path progression. Fortunately, StressWave measurement technology can measure the minute frictional effects of these early-phase issues and provide an opportunity to correct them before they lead to greater damage.

STRESS WAVE VS VIBRATION

It has been determined through many years of field and laboratory research that base friction and friction events generate high frequency (ultrasonic) sound emissions that can travel through machine structures and be detected by a suitably designed sensory apparatus. Curtiss-Wright provides patented sensors and recording technologies specifically for the purpose of measuring such signals. In order to differentiate such sound based signals from vibration, we refer to these signals as StressWave Energy.

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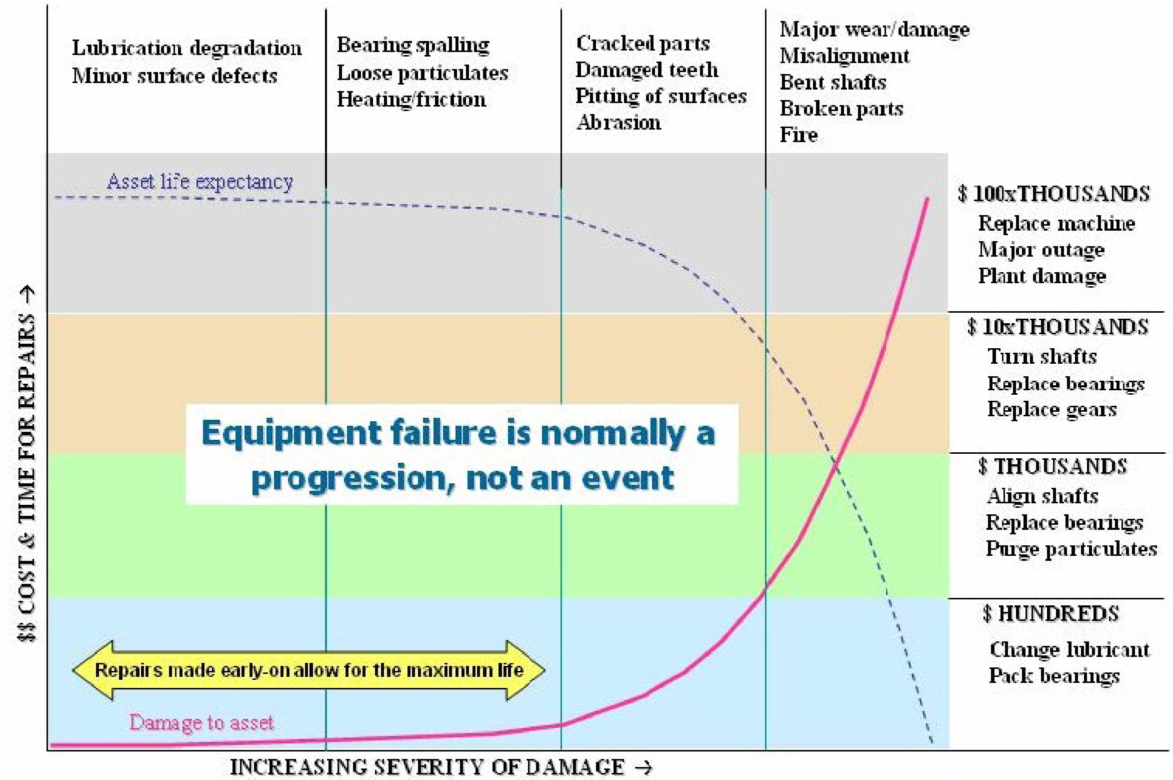

Figure 1: Diagram of Equipment Failture Progress

Vibration is the actual detectable cyclic physical motion of the machine, possibly in multiple axes; in high-mass machines, a lot of energy is required to induce vibration. Vibration in a machine system is either intentional or inevitable, like the way a bell vibrates when struck. StressWave Energy is generated by non-intended friction; if the same bell was scratched it would not vibrate, but would release ultrasonic stress wave signals from the applied friction.

USING STRESS WAVE MEASUREMENTS

Three broad classes of mechanical conditions have been found to generate stress wave sounds: base steady-state friction, load induced friction events, and damage induced impact events. Steady-state friction is the friction level generated by the machine when it has attained stable loading and speed, and thus is generally a constant amplitude/level signal, which only increases with general wear or lubrication degradation. Load induced friction events are momentary spikes in stress wave energy generated by sudden load changes causing lateral torque (gyroscopic progression), thus forcing a momentary broach in the lubricant barrier. Damage induced impact events are caused when moving components transit across surface damage, such as cracks, spalling, dents, and chips. This is also present when gears have damage or don't mesh smoothly.

All three classes of problem generate distinctive stress waves that can be recorded and analyzed to determine the magnitude, type, and source of the problem. Load generated friction events and damage generated impact events produce similar signal spikes, but damage based impact are repetitive whereas load induced spikes are not (and can be time-correlated to load changes.) Figure 2 is a simplified model of the stress wave energy (SWE) signal generated as the rolling element of a bearing transitions across an inner/outer race with a minor surface defect.

Unlike other methodologies, the use of StressWave monitoring does not require the development of a 'baseline' for typical machines, since SWE is a measure of friction and impact events. Since SWE is most effectively used as a continuous measurement, Curtiss-Wright uses a small, computerized data acquisition unit to take periodic data recordings from the sensors mounted on each machine. A typical data recording (called a DR, or digital record) can contain from 20,000 to 200,000 samples; these samples are analytically reduced to a set of representative values that indicate the overall operational condition of the machine. For complex machines with multiple bearings, shafts, or gear boxes, there may be multiple sensors, and their individual data sets can be merged

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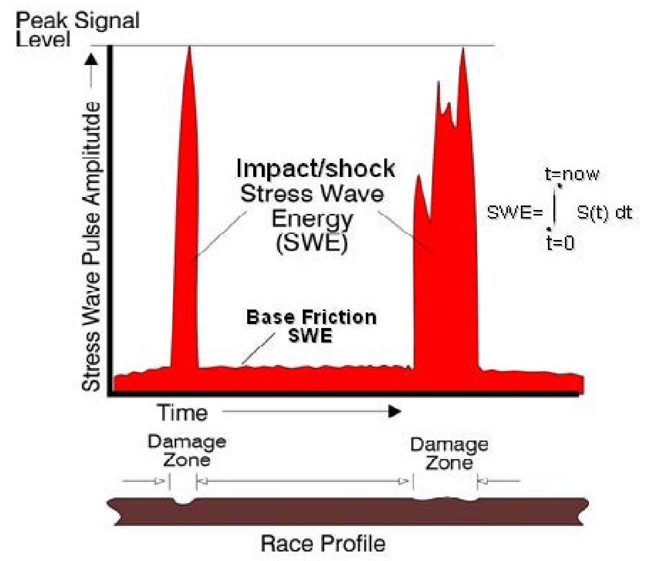

Figure 2: Stress Wave Histogram and Damage Representation

into an overall condition indication for the machine as a whole. On most machines, a DR is captured every 30 to 60 seconds and reduced to a basic set of indicators, and periodically the DR is retained and subjected to additional levels of analysis. All of this information is collected and stored in a server that retains several months of such data. In order to reduce or eliminate false positives (alerts triggered by transient indications), the analysis process uses successive readings to increase the confidence factor of a detected problem.

In most healthy machines there is no good reason for having high levels of SWE, especially SWE generated within the machine's bearings. Though there are 3 main types of SWE, in certain types of machines, such as reciprocating compressors, there will be other sources, such as the periodic impulses generated by the valves operating at the top of the compression cycle. Similarly in a pump, any cavitation present will generate detectable periodic SWE impulses. With these types of machines it is invaluable to define the expected periodic SWE impulse signals so that they can be differentiated from the defect-based periodic SWE impulses generated by actual physical damage.

BASIC ANALYSIS TOOLS

Two (2) basic methods are used to glean additional information to interpret the information contained in the DRs. In one method, the readings in the DR are sorted by energy levels, and a power density distribution histogram is computed.
In the other method, the data can be additionally run through an FFT (Fast Fourier Transform) to reveal spectral components at specific frequencies since periodic impulse events, such as those which are produced by physical damage, generate a repeated impulse signal in the DR. To manage variable speed machines, these are transformed into orders using the machines RPM value. Unlike with vibration based analysis, there will be no spectral components, regardless of the vibrational frequencies present, as seen in Figure 3; since StressWave monitoring deals only with ultrasonic frequencies, the normal vibrational frequencies of a machine are not registered in a healthy machine.

On the other hand, if damage exists, or if the machine has operational conditions that induce periodic impact events, then these signals will usually be clearly indicated in the spectral presentation, as seen in

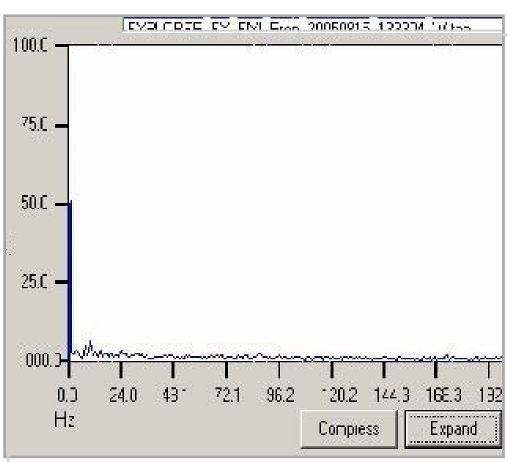

Figure 3: Operating Machine with No Damage (No Spectral Components)

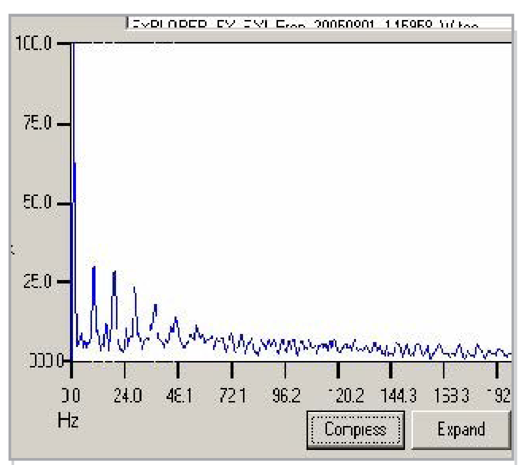

Figure 4: Operating Machine with Indications of Cavitation

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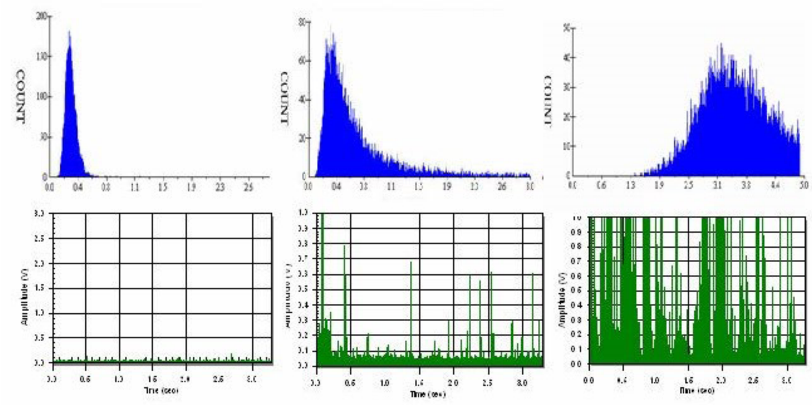

Figure 5: Stress Wave Histogram Showing Gradual Skewing Caused by Damages

the Figure 4. If the RPM of the machine is known, then the resulting spectral peaks can be directly correlated to a list of defect frequencies and expected frequencies, then evaluated concerning the possibility of damage. Multiple successive DRs taken hours apart are always compared to see if spectral components persist, and if they are changing in amplitude. This helps to eliminate false positives and to differentiate operation-induced signals from those generated by damage.

The use of an energy density distribution histogram of the DR's data also provides informative clues regarding the machine's operational condition, especially in the very early stages of degradation where the problem may merely be with lubrication. A machine in good condition will generate a flat, low amplitude, consistent SWE signal level, which, when plotted as a histogram, will produce a tall, narrow (small value of σ) plot with its modal value at low energy levels, like the plot in Figure 5. As wear develops and progresses, and as physical damage is generated, the histogram plot will develop a log skew. As things further degrade, the histogram will migrate to higher values for the mode, and the standard distribution (σ) will increase.

By combining the analysis of the SWE trend value with the FFT and histogram analysis of the 'raw' data, it is possible to make a reasonably accurate determination of a machine's overall operating condition, and to generate a set of numeric indices that can be trended and monitored over time as the machine progresses through its operational life span. These concepts are displayed in the graphs below. In Figure 5, the first left-most data set is from a machine in pristine condition, except for a very tiny crack in an outer race. Note the very low level periodic impulses in the DR, which is displayed in the plot below the histogram. The middle data set is for the same machine just prior to the replacement of the oil and additive package. The skew in the final right-most histogram was almost totally the result of skidding, slipping events that occur when a lubricant is degraded.

CORRELATING STRESS WAVE ENERGY WITH OPERATIONAL CONDITIONS

Because SWE is a real-time measure of the friction and stress being experienced by the machine components, its value is directly related to the operational loading (and changes thereof) being placed on the machine. In a fixed speed, constant load machine, the trended value of SWE will be a flat line until changes in friction cause the value to rise – these are usually caused by accumulated wear and damage. Figure

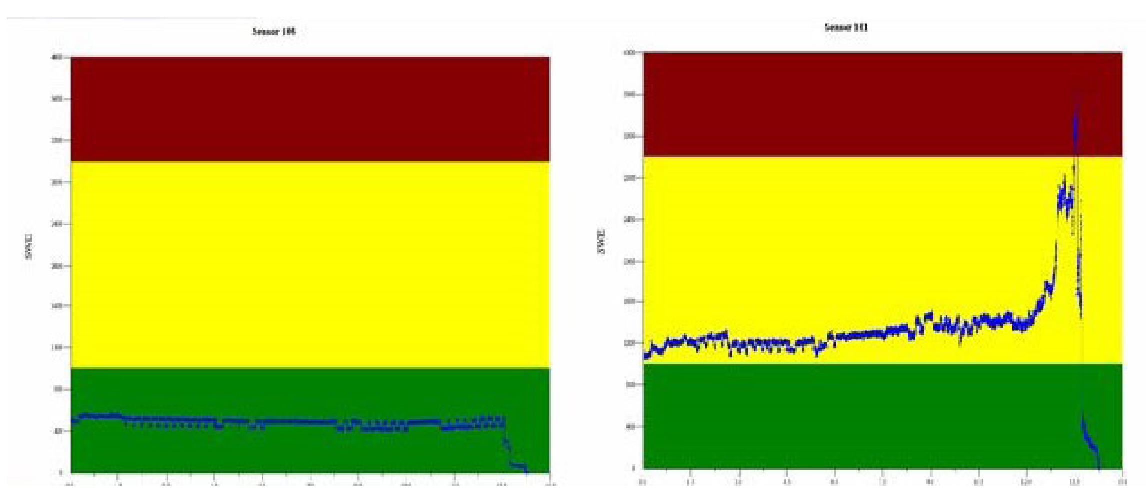

Figure 6: A Healthy Machine (Left) and the Faulty Machine (Right)

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6 shows two identical machines running a seeded fault test, in which one machine is intentionally damaged – in this case, the damage was the result of an insufficient quantity and inappropriate quality of lubricating oil. The two machines were then run in parallel until the failure of the faulty machine; the two plots below show the SWE levels in each machine through the many days of testing. As displayed in these graphs, the SWE levels on the faulty machine were immediately higher than its twin, and trended upward and accelerated as the machine accumulated actual wear and damage.

In a variable speed and/or variable load machine, the value of SWE will not be constant and stable; it will vary with the changes in load/speed. If a measurement of load, such as from the automation system that is controlling the machine, is available, then it can be correlated with SWE readings to determine the normal SWE levels expected at various degrees of loading. Alternatively, by observing a known to be healthy machine over a reasonable operating interval while recording SWE and some parameters that relate to loading, sufficient data can be collected to develop a profile of the machine's mean expected SWE for each point on the machine's operating load range. Figure 7 shows SWE from such a machine over a two week interval, as well as the resulting 'profile' generated from the data. As would be expected, the profile is not linear or flat, and shows that SWE is highest at the upper end of the operating range. This profile can then be used to judge the machine's degradation as time passes by comparing the current readings (indicated by the red "X" on the plot) with the ideal reading (as represented by the green profile plot).

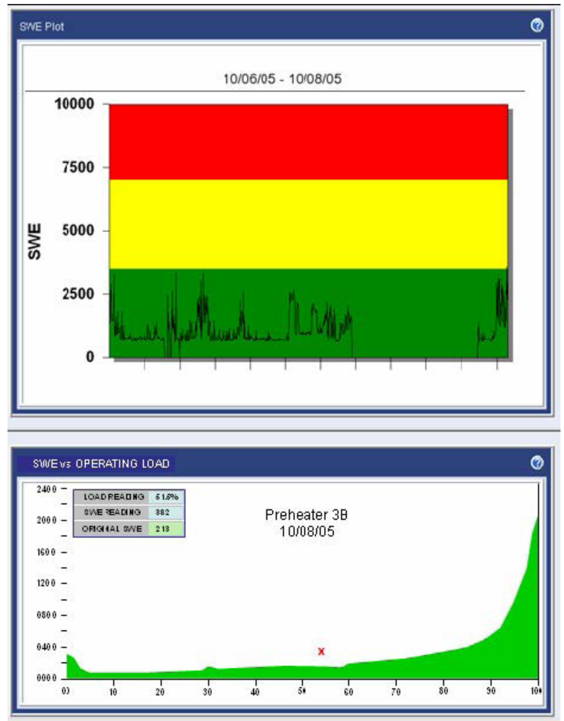

Figure 7: SWE In a Variable Load Machine

Figure 7 also gives a single-point (current operating load) comparison, but the same sort of data can be used to compare the machine over its operational range at different points in time. When new, machine's profile can be co-plotted with the profile computed one year later, two years later, or even right up to the data corresponding to the current operating condition. Figure 8 shows an example of a machine's profile computed at points in time a year apart over a three year span; it is clear that the current condition (the red bars) is degraded from the initial condition, particularly at the upper 25% of the operating load range of the machine. Additionally, if there are multiple, identical machines and it is important to know the comparative condition of each, comparing their operational profiles provides a convenient and clear way to identify the machine with the most wear and/or physical damage.

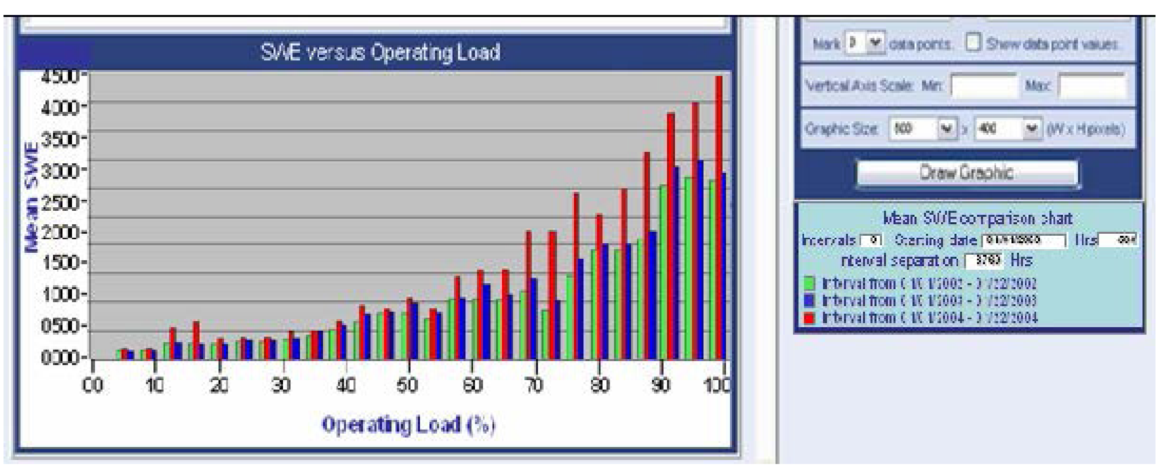

Figure 8: 3 Year Profile of a Machine's Condtion

ASSET MANAGEMENT OPPORTUNITIES

The ability to have real-time assessment of a machine's operational condition and operational profile is a valuable tool when making overall asset management and optimization decisions. This removes the need for costly routine preventive maintenance (PM) performed based on machine run time or elapsed calendar time. Under the traditional routine preventative maintenance method, it is not uncommon to perform repairs on a machine, only to have an equivalent machine break down immediately after the maintenance window. Knowing the actual operational condition of a machine allows a maintenance group to avoid making unnecessary repairs, to focus available funding and manpower on the assets that truly need them, and to have a better understanding of the level of repair work that will be required, allowing for the right parts, tools, and personnel to be available. Comparison of the individual operational profiles can also identify the best candidate for repairs in scenarios where time or budgets are limited.

Another opportunity provided by having a machine's profile is the ability to identify the operating load range that places the lowest stress levels on the machine; this information can then be used for asset life optimization purposes. Plant optimization is often done to attain lowest energy cost or highest throughput for the energy consumed; running a very expensive pump at it maximum loading in order to avoid running two to share the load may save a few dollars more in electric power, but might not be the optimal decision when the effect on asset life and the cost of repair/replacement are taken into account. A machine's profile may also enable the owner of a critical asset to delay its repair to a more convenient shutdown point by avoiding load levels that place high stress on the asset, such as changing a cruise ship to a schedule that avoided high speed segments between ports to enable the ship to nurse its propulsion system until the next scheduled dry dock.

SUMMARY

StressWave analysis is a proven and tested technology for measuring the real time friction and damage being expressed within a machine. Unlike other technologies, StressWave analysis is sensitive to the dynamics of the machine but not vulnerable to its mechanical vibrations, even to the minute level of sensing changes in lubrication effectiveness. StressWave analysis provides early-stage indication of machine degradation and provides a trend-able, measurable value that can be tracked through the life of the machine. When combined with machine specific information, such as bearing fault frequencies, StressWave analysis can provide specific indications about the source of detected faults. Additionally, by providing real-time, related operational measurements stress wave aids in achieving asset optimization. The features of StressWave analysis, combined with other technologies, provide the most complete and comprehensive indication of the operational condition of a machine.

CONTACT INFORMATION:
1350 Whitewater Drive, Idaho Falls, ID 83402
sscheeren@curtisswright.com | +1.954.253.8588