# Sensor reliability impact on predictive maintenance program costs

## Abstract

Accelerometers with lower mean time between failures (MTBF) values result in higher costs for permanently installed vibration sensor applications. The additional cost of purchasing accelerometers with a low MTBF could add as much as $60 to the total purchase cost of an accelerometer. All purchasers desire to have a total lower cost when buying accelerometers. By taking the MTBF and manufacturing quality into account when making an accelerometer purchase, buyers can achieve a total lower cost of ownership.

## Mean time between failures

Mean time between failures (MTBF) represents the average expected time that will elapse between failures of like units under like conditions. Standard methods to calculate the MTBF have been developed. Purchasers should consider the MTBF of an accelerometer before buying them. Accelerometers with a low (short) MTBF mean higher costs due to the manpower for troubleshooting and replacement of bad accelerometers and lost data associated with the more frequent failures.

The Department of Defense, through the Air Development Center in Rome, NY developed a calculation "cookbook" to be used for electronic systems and circuits. It is the Military Handbook MIL-HDBK-217. This document has gone through revisions over the years, but it still provides very good guidance for computing the MTBF for hermetically sealed electronic circuits. Bell Laboratories also developed a standard method for computing MTBF known as Belcore. The Belcore standard is widely used in the communication and computer industry for the computation of MTBF. Regardless of which standard is used for doing "cookbook" computation of the MTBF, they are useful for comparison of designs before they are reduced to practice.

Once equipment has been fielded, measurements can be made of the MTBF of installed equipment. The simplest expression of MTBF for fielded systems is MTBF = total time exposure / # failures. For example, if 100 units were operated for 1,000 hours before the first unit failure were experienced, the MTBF would be 100 (units) x 1,000 hours per 1 failure, or MTBF = 100,000 hours. If, however, there had been 5 unit failures during that same time period, the resulting MTBF would be 20,000 hours (100,000/5).

## Causes of accelerometer failures

Problems associated with the internal electronic amplifier of Integrated Electronic Piezoelectric (IEPE) accelerometers are the primary reason accelerometers fail. Amplifier board failures are sometimes due to external causes, such as excessive powering voltage or an electrostatic discharge (ESD) to the accelerometer. Both of these conditions often occur during the initial installation of accelerometers. Long-term failures are usually associated with circuit board connection faults (bad solder joints), components drifting in value or failing, contamination of the circuit board causing component failures, or exposure of the accelerometer to temperatures beyond the accelerometer design.

Faulty connections of electrical components to the solder pads of a printed circuit board will cause an accelerometer to fail. This is no different than any other electronic item. "Cold" solder joints are a known failure mode for electronic circuits. They are formed when the solder fails to reach a proper melting temperature during manufacture. Hybrid circuit boards are usually run through a wave soldering process or an oven. If the process is not adjusted correctly, the solder does not melt and run into the joints properly. Heat cycling over time causes the connection to develop high resistance by forming an oxidation layer. Therefore, it is important to properly set the heat levels in soldering operations and to use the right amount and type of solder. This will minimize the occurrence of faulty joints. Accelerometer manufacturers try to preclude any oxidation potential by filling the accelerometer with a chemically inert gas such as nitrogen that will not react with the solder.

The interface between the accelerometer and its mating connector can also be a source of connectivity problems. Many connectors that have been used for years have tin-plated contact surfaces. Tin in connectors will be subject to "fretting" and cause unreliable contacts[1]. One solution to this problem is to use gold-plated contact surfaces in instrumentation wiring. It has been considered a "best practice" in instrumentation to use gold-to-gold in connectors when low-level voltages must be transmitted through connectors. The gold-to-gold connection will aid in producing a total lower cost for accelerometer installations.

Circuit board component failures will cause accelerometers to fail. Each component used in the circuit will be repeatedly stressed over its life by the voltages and temperatures imposed on it. The electron flow within the material will cause any impurities to become focused on that area of the part resulting in component failure. Using high-quality, screened parts will reduce these kinds of failures and produce a total lower cost for accelerometer installations.

Contamination ingress will cause accelerometers to fail. The contaminants cause a chemical reaction with circuit board component parts resulting in a change in values of resistance or capacitance. Semiconductors will lose their characteristics of amplification due to the entry of contaminants. The best defense against contamination is a good hermetic seal. Hermetic sealing can best be assured through helium leak testing (HLT). HLT is the industry standard for electronic circuit leak testing. It is the only way to accurately determine whether seals are truly hermetic. Guaranteeing hermeticity through HLT will result in an accelerometer with a total lower cost.

Poorly designed and protected accelerometers will not withstand the test of time. Mechanical parts must be able to tolerate the physical stresses of use and abuse. The electrical circuits must be properly protected against normal use and handling conditions. Typical industrial accelerometers are designed to withstand up to 5,000 g's of shock. These high levels can be produced when an accelerometer is dropped onto steel. High shock levels can produce high voltages out of the crystal stack that can exceed the withstanding voltage of the FET in a typical Integrated Electronic Piezoelectric (IEPE) accelerometer amplifier. Static electricity build-up on the person of someone handling the accelerometer could damage it if the circuit is not properly protected. Quality manufacturers will install protection in the circuitry of the IEPE accelerometer to protect it against many of these conditions resulting in an accelerometer that yields a total lower cost to the user.

Accelerometers that are exposed to conditions beyond their design limits will fail sooner. IEPE accelerometers are designed to be connected to a powering circuit that has a constant-current diode in series with the DC power supply. Wiring an accelerometer directly to a DC power

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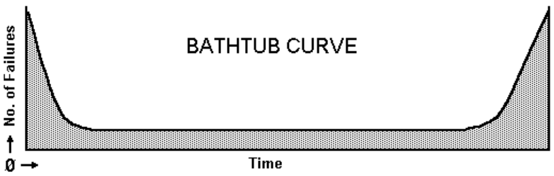
[1] Contact Problems Due to Fretting and Their Solutions, Piet van Dijk & Frank van Meijl, AMP Journal of Technology Vol. 5 June 1996

supply and not using a constant-current diode will usually result in an immediate failure. Wiring an accelerometer backward, that is, with the negative supply voltage going to the positive terminal, will usually result in an immediate failure also. High quality sensors employ reverse-wiring protection and over-current protection to guard against these types of failures. Operating accelerometers above their maximum design temperature will cause degradation and eventual failure. There is no protection for high temperature operation.
Premium-grade accelerometers will be designed to operate when exposed to almost all of the above conditions. Excessive temperature is the one condition that cannot be accommodated in a design. While an accelerometer might be able to be subjected to excessive temperature once in a while and survive, there is no guarantee that it will continue to operate untroubled for many years. Usually, operating above the recommended maximum temperature will dramatically shorten the lifetime of an accelerometer.

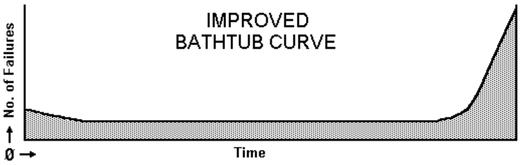
## The "bathtub" curve, "infant mortality" and "root cause analysis"

Here is an example of a "bathtub" curve showing "infant mortality," from RG Associates[2]. "The following graph, commonly called the ‘bathtub curve,’ illustrates the life or reliability of products. Some fail in their infancy (infant mortality) and those that survive, should go on to live a long trouble-free life before finally wearing out."



The bathtub shape of the curve originates from the fact that a plot of the number of unit failures versus time results in that kind of curved shape. The curve also resembles the mortality plot that would result from an actuary when the number of deaths versus the age of people is plotted. Mortality data indicates that people at the youngest ages (infants) die at a rate higher than adolescents or adults. Consequently, the failures occurring early in the life of physical systems are called "infant mortality."

For humans, if expectant mothers get good "prenatal" care then the infant mortality rate can be reduced. This would result in an improved bathtub curve. The same is true for electronic and mechanical systems. While humans call it pre-natal care, engineers call it "root cause analysis." An analysis of the causes of early demise can result in "lessons learned" that can be applied to other systems (or infants). Electronic component pre-aging and environmental stress screening can further reduce component infant mortality.



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[2] http://www.rgassocs.com/page5.htm as of May 12, 2006.

## The role of ISO 9001

ISO 9001 establishes a process for companies to document their processes and then ensures that these processes are followed. It sets forth a pattern that companies can use to implement root cause analysis of system and equipment failures, but does not insure that rigorous root cause analysis is applied to process failures. It also addresses the controls over manufacturing contamination in the manufacturing process and component quality.

ISO 9001 is a part of a family of standards for companies to implement for certification of their processes and procedures. ISO 9001 does not, by itself, ensure that a manufacturer is applying "lessons learned" to their designs. What ISO 9001 does is ensure that companies can manufacture items in a consistent fashion according to their processes and procedures. If those processes and procedures are never changed to reflect the lessons learned from failures, then there will be no improvement in the quality or, therefore, the MTBF of accelerometers.

## The cost of installed accelerometer failures

Every time an accelerometer fails it costs time and effort to diagnose the failure and replace the accelerometer. This diverts skilled manpower from their primary task of prognostication in order to test and replace failed sensors.

## Locating faulty accelerometers

For this analysis we will consider permanently installed accelerometers because they are the ones most difficult to diagnose and replace. The portable accelerometers can be readily changed out with little or no investment of time, so we will not investigate portable accelerometer failure.

There are many indicators of faulty accelerometers. The bias output voltage (BOV) can be outside the normal range. The data can contain serious "ski slopes" at low frequencies. The spectrum may "flat line" because of no signal. Whatever the cause, it usually means that the predictive maintenance vibration technician must take time to determine that all cable connections are tight and clean, that the accelerometer is solidly mounted, and that the cable is not broken.

It has long been held that connection failures account for at least half of electrical system problems. This is the general consensus of people that work with electrical and electronic systems. Consequently, the first thing a vibration technician usually does when a vibration reading has a problem is to determine whether the fault is in the cabling. Depending on the accessibility of the accelerometer, this could take two to thirty minutes. It might involve changing accelerometers, cleaning connections, returning to the shop at least once for spare cables, or any of a myriad of other possible expenses of time.

## Failed sensor replacement

While there may be some disagreement, it is likely that it will involve at least one person for at least 30 minutes of time to determine that an accelerometer is not functioning correctly. This time will increase when the accelerometer is mounted in a position that involves "high work", is on a cooling tower fan, is in a hazardous classified area, or requires any kind of work permit to be written. It is quite possible that it could take upwards of one man-hour to determine that an accelerometer has failed and replace it.

Then there is the additional time and expense involved in returning accelerometers to the manufacturer. Telephone calls need to be made, return authorizations obtained, bad accelerometers packaged, and shipping papers prepared. Then there is the shipping cost itself. This process could add 5 to 30 minutes per accelerometer to the original time taken to find, verify and replace the failed accelerometer.

## What effect does high "infant mortality" have on PdM costs?

Early failure rates for accelerometers means that Predictive Maintenance technicians will be quickly faced with learning to diagnose accelerometer problems. It will also make those users have to spend valuable time early in a new installation just trying to sort out the "bad" accelerometers from all the fresh data that must be analyzed.

There are many machine problems that can appear to look the same as some accelerometer failures. PdM technicians will quickly lose confidence in the newly installed accelerometers as they sort through the data. The direct costs of these early accelerometer failures are those associated with finding and replacing the accelerometers. The indirect, and difficult to quantify, costs are those that cause valuable time for data analysis to be lost when working with bad accelerometers. The ultimate cost to the vibration PdM program is that it will diminish the return on investment (ROI) of the PdM effort and may cost the support of upper management because of a loss of confidence.

## MTBF rates translate to expected costs

To give some idea of the relative cost differences due to various MTBF rates, we will use an example installation of 300 accelerometers. We will further assume that each time an accelerometer fails it takes a total of one man-hour to isolate the failure, replace the accelerometer, and perform all the tasks necessary to return the unit for a warranty replacement. An example of this process might be as follows:

1. Test the accelerometer for BOV and signal
2. Obtain cold work permit (high work permit if over 6' above floor
3. Shut down the machine
4. Lock-out and tag-out the machine
5. Access and remove the accelerometer
6. Replace the accelerometer with a "spare" from stock
7. Test the new accelerometer for BOV and signal
8. Remove the lock-out and tag-out
9. Restart the machine
10. Package the faulty accelerometer
11. Prepare shipping document for faulty accelerometer
12. Shipping department or purchasing department contacts manufacturer for warranty replacement
13. Receive replacement accelerometer into "stock" room

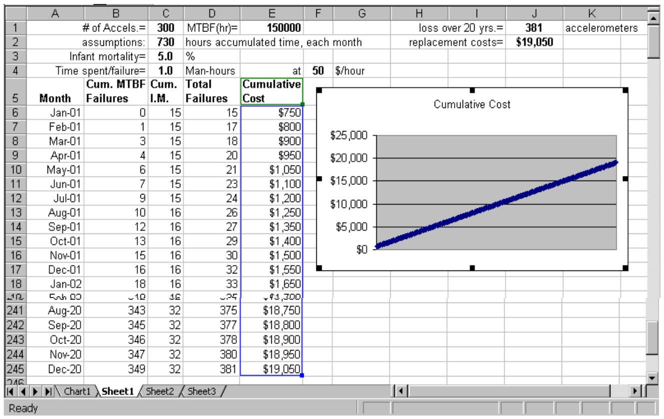
In addition, we assume that the fully burdened cost of this time is $50 per hour. This assumption is also quite conservative since it only amounts to $100,000 per year per employee. Most companies have fully burdened rates that are in the $70 to $80 range.

The project "life" will be estimated as 20 years. This assumption is based on the general expectation in industry that machinery and control systems will be installed for at least that period of time before the possibility of total replacement would be considered. It also represents the general period of time used for depreciation of capital equipment.

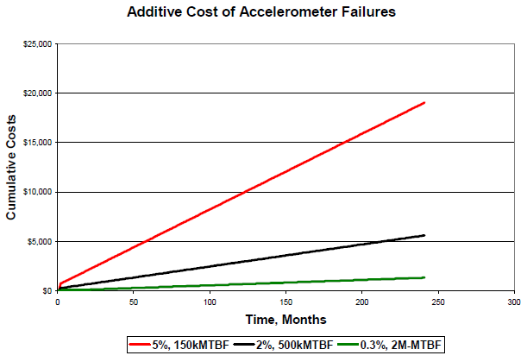
We will consider infant mortality (I.M.) as occurring every N sensors, where
N = 1/I.M.%. Therefore, a 5% I.M. rate means that for each twenty new accelerometers 1 will fail. Further, our model will assume that each time the total exposure of accelerometers reaches the MTBF one accelerometer will fail. A spreadsheet example is illustrated here.

In the first example, we assume a 5% infant mortality and 150,000 hour MTBF. This is comparable to what would be experienced with poor quality accelerometers. The total lifetime cost to the project owner would be $19,050.

In another case, we assume the infant mortality to be 0.3% and the MTBF to be 2,000,000 hours. This is what could be expected for reasonably good quality accelerometers. The total lifetime cost to the project owner would be $1,350.



|  | A | B | C | D | E | F | G | H | I | J | K |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 |  | # of Accels.= | 300 | MTBF(hr)= | 150000 |  |  | loss over 20 yrs.= |  | 381 | accelerometers |
| 2 |  | assumptions: | 730 | hours accumulated time, each month |  |  |  | replacement costs= |  | $19,050 |  |
| 3 |  | Infant mortality= | 5.0 | % |  |  |  |  |  |  |  |
| 4 |  | Time spent/failure= | 1.0 | Man-hours | at | 50 | $/hour |  |  |  |  |
| 5 | Month | Cum. MTBF Failures | Cum. I.M. | Total Failures | Cumulative Cost |  |  |  |  |  |  |
| 6 | Jan-01 | 0 | 15 | 15 | $750 |  |  |  |  |  |  |
| 7 | Feb-01 | 1 | 15 | 17 | $800 |  |  |  |  |  |  |
| 8 | Mar-01 | 3 | 15 | 18 | $900 |  |  |  |  |  |  |
| 9 | Apr-01 | 4 | 15 | 20 | $950 |  |  |  |  |  |  |
| 10 | May-01 | 6 | 15 | 21 | $1,050 |  |  |  |  |  |  |
| 11 | Jun-01 | 7 | 15 | 23 | $1,100 |  |  |  |  |  |  |
| 12 | Jul-01 | 9 | 15 | 24 | $1,200 |  |  |  |  |  |  |
| 13 | Aug-01 | 10 | 16 | 26 | $1,250 |  |  |  |  |  |  |
| 14 | Sep-01 | 12 | 16 | 27 | $1,350 |  |  |  |  |  |  |
| 15 | Oct-01 | 13 | 16 | 29 | $1,400 |  |  |  |  |  |  |
| 16 | Nov-01 | 15 | 16 | 30 | $1,500 |  |  |  |  |  |  |
| 17 | Dec-01 | 16 | 16 | 32 | $1,550 |  |  |  |  |  |  |
| 18 | Jan-02 | 18 | 16 | 33 | $1,650 |  |  |  |  |  |  |
| 241 | Aug-20 | 343 | 32 | 375 | $18,750 |  |  |  |  |  |  |
| 242 | Sep-20 | 345 | 32 | 377 | $18,800 |  |  |  |  |  |  |
| 243 | Oct-20 | 346 | 32 | 378 | $18,900 |  |  |  |  |  |  |
| 244 | Nov-20 | 347 | 32 | 380 | $18,950 |  |  |  |  |  |  |
| 245 | Dec-20 | 349 | 32 | 381 | $19,050 |  |  |  |  |  |  |



While some might say that the 5% infant mortality rate is too high, we can look at one more example and assume a 2% infant mortality with a 500,000 hour MTBF. The results indicate a 20-year cost of $5,600. This is still $4,200 above the lower example and a $14 per accelerometer additional cost over the 20-year project example.

Table 1, below, summarizes the cumulative costs over a twenty-year period. The poor quality accelerometers result in a 20 year cost for identifying and replacing the accelerometers at about $19,000. While the similar costs for good quality accelerometers runs a little under $1,400 over 20 years. Neither example takes into account the time value of money or the effects of inflation.

The "price" paid for the poorer quality in this example is nearly $18,000 due to the difference between lifetime costs for high quality versus low quality. That works out to almost $60 per accelerometer. Even if we inflation is taken into account, the net present value of this analysis would not change as the rate would have to be applied to all numbers. It also does not take into account the long-term aggravation of having to replace almost 400 accelerometers over the 20-year span of the installation.

Table 1- Added cost factors for various quality levels

| Project: | 300 accelerometers, 20-year cost | | | | |
|---|---|---|---|---|---|
| Quality | "Infant" mortality | MTBF in practice | Project cost added | Cost add'l per accelerometer | Accelerometers replaced |
| Low | 5.0% | 150 K-hrs. | $19,050.00 | $63.50 | 381 |
| Moderate | 2.0% | 500 K-hrs. | $5,600.00 | $18.67 | 113 |
| High | 0.3% | 2 M-hrs. | $1,350.00 | $4.50 | 27 |

The above table summarizes how accelerometer quality and, hence, MTBF enters into the cost of purchasing accelerometers. It is important to remember that the above summarized costs are the costs to the owner and assume that all accelerometers are replaced for zero cost. This is equivalent to having accelerometers with a "lifetime" warranty against failures. The additional cost per accelerometer is also independent of the original purchased cost of the accelerometers for the project. The costs summarized are those that accrue to the purchaser after the sensors are bought.

## Appendix

MIL-HDBK-217 is a useful reference for computing MTBF for Integrated Electronic Piezoelectric (IEPE) accelerometers. Most accelerometers contain hybrid circuit boards with electronic components and the accelerometers are usually hermetically sealed. If the accelerometers are hermetically sealed, then MIL-HDBK-217 can be used to make an initial determination of the likely MTBF for the accelerometers. The handbook uses the term "Total Hybrid Failure Rate" and identifies it as $\lambda_\rho$.

### Total hybrid failure rate ($\lambda\rho$)

$\lambda_\rho = [\Sigma N_C\lambda_C]\,(1 + 0.2\,\pi_E)\,\pi_F\,\pi_Q\,\pi_L$ failures per 1,000,000 hours

Where $N_C$ = number of each particular component

$\lambda_C$ = failure rate of each particular component

$\pi_E$ = environmental factor

$\pi_F$ = hybrid function factor

$\pi_Q$ = quality (screening) factor

$\pi_L$ = longevity (experience) factor

N is determined simply from the part or connection count; all other factors are determined through reference to MIL-HDBK-217 for the particular component or element.

Table 2 – Values for 786A accelerometer

| N components/elements | 60° C |
|---|---|
| 48 connections | .018122 |
| 4 plated through holes | .000041 |
| 1 crystal | .0058 |
| 1 bipolar transistor | .00029 |
| 1 FET | .0135 |
| 3 diodes | .00731 |
| 3 capacitors | .016082 |
| 5 resistors | .00363 |
| Individual $N_C\lambda_C$ | .064775 |

**Calculated total hybrid failure rate (786A):**

@ 60° C

$\lambda\rho$ = [.064775] 70.18

= 4.5459 / 106 hrs

= 4.5459 per $10^6$ hrs

= 219,978 hrs MTBF

## Field failure experience

### Example 1

Manufacturing environment with production lines where the temperature of the 786A accelerometers was approximately 60°C

| | |
|---|---|
| Total installed number of accelerometers: | 270 |
| Total operating time of accelerometers: | 3 years |
| Total number of actual failures: | 3 units |

(270 units) x (8,760 hours) x (3 years) = 7,095,600 operating hours
MTBF in practice = 7,095,600/3 = 2,365,200 hours

### Example 2

O.E.M. application at unknown temperatures for installations of the 786A on a variety of general manufacturing and processing machines

| | |
|---|---|
| Total installed number of accelerometers: | 627 |
| Total operating time of accelerometers: | 3 years |
| Total number of actual failures: | 7 units |

(627 units) x (8,760 hours) x (3 years) = 16,477,560 operating hours
MTBF in practice = 16,477,560 /7 = 2,353,737 hours

### Example 3

O.E.M. application at unknown temperatures for installations of the 786A on a variety of general manufacturing and processing machines

| | |
|---|---|
| Total installed number of accelerometers: | 385 (786A) |
| Total operating time of accelerometers: | 44 months (3.67 years) |
| Total number of actual failures: | 1 unit |

(385 units) x (8,760 hours) x (3.67 years) = 12,366,200 operating hours
MTBF in practice = 12,366,200 /1 = 12,366,200 hours

### Example 4

Wilcoxon tracks returned accelerometers. The percentage of accelerometers returned in any given year is less than 0.3% of those produced. This quality level is commensurate with an MTBF of nearly 3,000,000 hours.