Simple Time-to-Failure Estimation Techniques for Reliability and Maintenance of Equipment

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Introduction

In 1979, MIT produced a report on maintenance with a focus on tribology. They estimated that $200 billion US dollars were spent on the direct costs associated with reliability and maintenance (R&M) [1]. At the time it was also estimated that over 14% of the 1979 gross domestic product (GDP) was lost opportunity due to improper R&M practices [2]. This level continued to increase as the industrial infrastructure aged, as well as other reliability-based reasons, to over 20% of the US GDP, or over $2.5 trillion in lost business opportunity [3]. This is greater than all but the top three economies in the world! At this time it is estimated that the R&M industry is approximately $1.2 trillion in size with up to $750 billion being the direct cost of breakdown maintenance (reactive) or generally poor, incorrect or excessive practices [4].

The primary cause of the loss is that over 60% of maintenance programs are reactive, and the number is growing [2], which includes those programs which were initiated and later failed due to "maintenance entropy," or collapsing successful programs where the significant paybacks are no longer seen. At this time over 90% of maintenance initiatives fail, 57% of computerized maintenance management system (CMMS) applications fail, and over 93% of motor management programs fail [4]. The primary reason is that the present business mindset calls for immediate improvements, whereas it normally takes 12 to 24 months for a supported program to take hold and begin to show results—a rule of thumb that applies to all business practices.

Proper R&M best practice processes have a direct impact on equipment availability, throughput capacity, and spare inventories. In addition, the US Department of Energy's Federal Energy Management Program has published that proper R&M can improve energy costs by an average of 5 to 20% [5]. For example, if we were to just maintain electric motors, alone, it would yield annual energy savings of up to 122 billion kWh and greenhouse gas emission reductions of over 74 megatons per year [6]. When expanded to all maintenance opportunities, the impact is significantly larger.

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One of the more troublesome parts of any R&M program is the need to provide a prediction of the time that equipment will fail. Such is the paradox of testing and inspections related to a practice referred to as predictive maintenance (PdM). In PdM, the predictions almost solely rely upon the experience of the technician and accuracy requires an extremely significant amount of information and pure luck, a primary reason why condition-based programs fail. A more accurate description of how such findings are handled is that the technician or engineer estimates a time to failure, a process in which industrial and reliability engineering rules apply.

Tools for Time-To-Failure Estimation (TTFE)

There are some basic mathematical tools needed for providing answers for the analysis. If used for planning and scheduling scenarios, the formulae are used with the mean time between failures (MTBF), mean time to repair (MTTR), and their associated failure and repair rates. In the case of TTFE, the formulae are used along with mean time-to-failure (MTTF) and the mean time for corrective maintenance (M_{CT}) for fault detection and the combined use of planning and TTFE methods for redundant systems [7]-[9].

The first important formulae to consider (1) are the MTTF and the failure rate (2), determined after detection of a fault during PdM monitoring.

$$\text{MTTF} = (\textstyle\sum \text{period between detection and failure})/n_f, \quad (1)$$

where the period between detection and failure is the total sum of the time between detection and failure for all failures and n_f is the number of failures.

$$\text{MCT} = (\textstyle\sum \text{Time for repair})/n_f, \quad (2)$$

where time for repair is total sum of the time repairing the faults in (1) and n_f is the number of corrective maintenance tasks.

These formulae provide us with the basic information that is required for the MTTF and M_{CT} for the TTFE calculation. For example, consider the results shown in Table 1 after contamination is detected on a winding and the motor progresses to a winding short. Therefore, the MTTF would be (101 weeks/5) = 20.2 weeks and the M_{CT} would be 0.73 weeks.

The next formula required is the failure rate (λ) which is simply 1 divided by the MTTF:

$$\lambda = 1/\text{MTTF} \quad (3)$$

Finally, the next equation gives the chance for failure over time, or the modified inherent unavailability (F_U).

$$F_U = 1 - (D)(e^{-t\lambda}), \quad (4)$$

where t is the time being evaluated to determine chance for failure in that time period based on the failure rate (λ) and D is the severity modifier (defined next). Inherent unavailability is a standard industrial engineering formula.

Table 1. Statistics of Motor Winding Failures Caused by Contamination.

n_f (Corrective maintenance task)	Period between detection and failure (weeks)	Time for corrective maintenance tasks (weeks)
1	16	0.43
2	22	1.0
3	20	0.2
4	25	0.8
5	18	1.2
SUM =	101	3.63

The Severity Modifier (*D*)

In order for an accurate determination of the Inherent Unavailability, a modification must be included based upon the severity of the fault detected. The simplest method for determining the severity modifier, D, for the simplified TTFE method, is to look at the slope of the change between the trended data prior to the point of detection and at the point of detection. The time between measurements must be presented in the same terms as the MTTF or failure rate (i.e.: hours, days, weeks, etc.).

For instance, if a quarterly polarization index measurement decreases from 5.4 to 3.2, and the failure rate is determined in weeks, then the slope would be 2.2/12 = 0.183. D would be equal to one minus the slope and would be the multiplier times the inherent unavailability, in this case $D = 0.817$. This helps determine at what point the failure exists on the failure curve (see Figure 3), as the fault must be considered to have initiated between the past measurement and present measurement. The greater the slope of change, the more severe the fault, with the purpose of D being the adjustment to the chance of failure determined by inherent unavailability.

There are other methods of determining the severity modifier for different testing methods or experience that will not be addressed in this article.

Understanding Series and Parallel Availability

While not used for TTFE, in most cases, an understanding of series and parallel reliability can be used, along with MTTF and M_{CT}, in order to evaluate the strategies around redundant equipment. The reliability function, F, also known as the inherent availability, is expressed as

$$F = e^{-t\lambda}, \quad (5)$$

where t is the time being evaluated and λ is 1/MTBF.

The series, F_S, and two-system parallel, F_P, (systems F_A and F_B) availability functions can be expressed as follows:

$$F_S = (F_1)(F_2) \ldots (F_n), \quad (6)$$

$$F_P = (F_A + F_B) - (F_A)(F_B). \quad (7)$$

The parallel availability for 3 or more identical systems is expressed as

$$F_P = 1 - (1 - F)^n. \quad (8)$$

With this information, the impact of system redundancies can be examined. For the purpose of this example, consider the following redundant pump system. One pump is used as an idle spare (off-line in normal operation, brought on line when the primary is removed for repair or trips) while the other pump (primary) runs constantly at 6000 hours per year. In the example, the numbers are based upon a calendar time of 6000 hours per year and whether the spare is operating or idle. A review of the history of the pumps reveals the following:

Primary Pump

The pump seal has had to be replaced twice over five calendar years of operation (30 000 hours), the M_{CT} is determined as 96 hours, with the last failure at the end of year five (2 failures/(30 000 hours – 192) = 6.7×10^{-5} failures/hour); over the same period, the bearings have failed in the motor once at 22 000 hours with the same M_{CT} (96 hours) (1 failure/22 000 hours = 4.5×10^{-5} failures/hour).

Idle Spare

Upon operation of the spare motor, the bearings became noisy at a calendar time of 13 500 hours, because of false brinelling (1 failure/13 500 hours = 7.4×10^{-5} failures/hour), and the spare motor shows a low insulation resistance level at 20 000 hours (1 failure/20 000 hours = 5.0×10^{-5} failures/hour). These numbers are both based upon the calendar time (6000 hours per year) whether the spare is operating or idle, because the false brinelling and insulation resistance issues as both are caused from the pump sitting idle. The running spare 288 hour reliability numbers are based upon the failures detected or occurring during the run time of the spare.

At the five year point, in the primary pump: the failure rate of the seal is 6.7×10^{-5} failures per hour; the failure rate of the bearings is 4.5×10^{-5} failures per hour. The idle spare has a calendar time bearing failure rate of 7.4×10^{-5} failures per hour and a calendar time winding failure rate of 5.0×10^{-5} failures per hour. The total corrective maintenance time (operating time of the spare) is 288 hours. This means that there is an operating failure rate of 6.9×10^{-3} failures per hour with the other failure rates related to the idle time of the pump.

If evaluating the availability of each machine, the resistance to failure graph would look like that in Figure 1 (1.00 = 100%). The running primary is in real time with the spare pump being demonstrated as both idle and running. When idle, the spare pump follows the red curve in comparison to the real time of the running primary (giving the chance that it will start if the primary fails). However, the actual operating reliability of the idle spare follows the green curve, or running spare, which is its resistance to failure during the 288 hours that the primary pump is out for corrective maintenance.

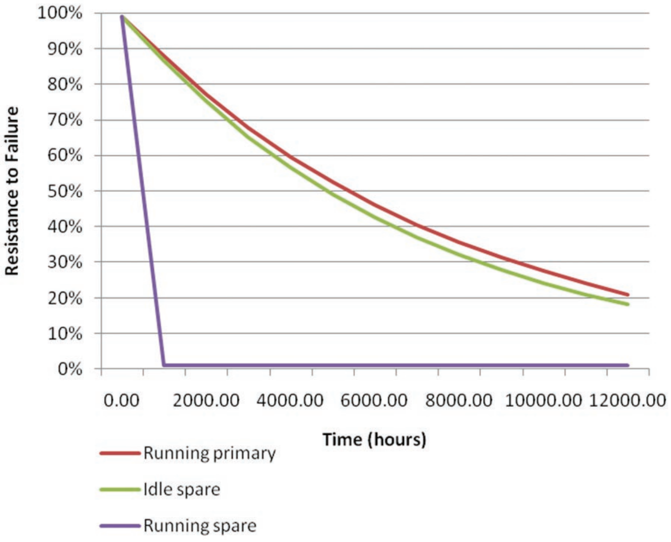

Figure 1. Inherent availability of parallel pump components.

Now, the difference is that the times are based upon the actual time following each repair. Therefore, the representation that each of the lines show in the graph is not the actual representation of how they relate to each other, with the exception of when they were originally installed or if they failed and were repaired at the same time. Using the above information, the availability of the complete system can be modeled if the total running hours for each pump is known. Here is how a scenario would be evaluated with the following information: 5000 hours operating time with the primary pump and 96 hours of operation with the spare that has been idle a total of 2500 hours.

The availability of the primary is calculated by taking the availability of the seal and the bearing, based upon 5000 hours, and multiplying them. In this case, the availability is 0.57 (57%). The availability of the secondary is calculated using 2500 hours as idle, as in item 1, and 96 hours for operation; these results are then multiplied, giving a resulting availability of 0.37 (37%). Both are now considered as a parallel system in which (0.57 + 0.37) – (0.57)(0.37) = 0.73 or 73%.

However, if both pumps are considered to be primaries, switching at the beginning of each week, then the evaluation will be based upon both pumps having the same failure rate as the primary. The total linear time for the evaluation is about 5000 hours or 10 months.

If the same scenario is taken, where Primary A has been alternating and running for 5000 hours and Primary B has been alternating and running for 2500 hours since the last repair, the availability at that time (20 months for Primary A and 10 months for Primary B) will be 0.57 for Primary A and 0.76 for Primary B, resulting in a system reliability of (0.57 + 0.76) – (0.57)(0.76) = 0.90 or 90%.

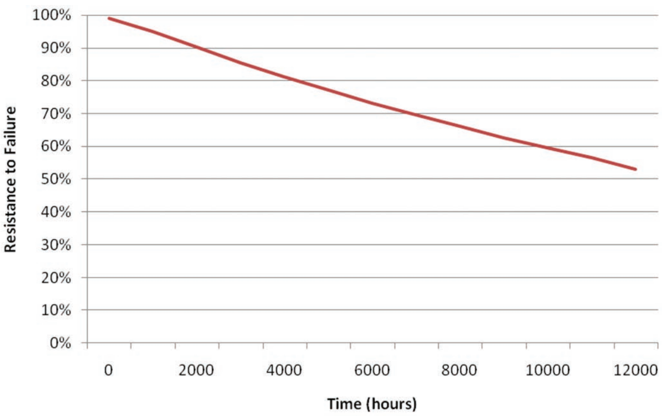

Figure 2. Failure curve of Primary A for bearing detection scenario.

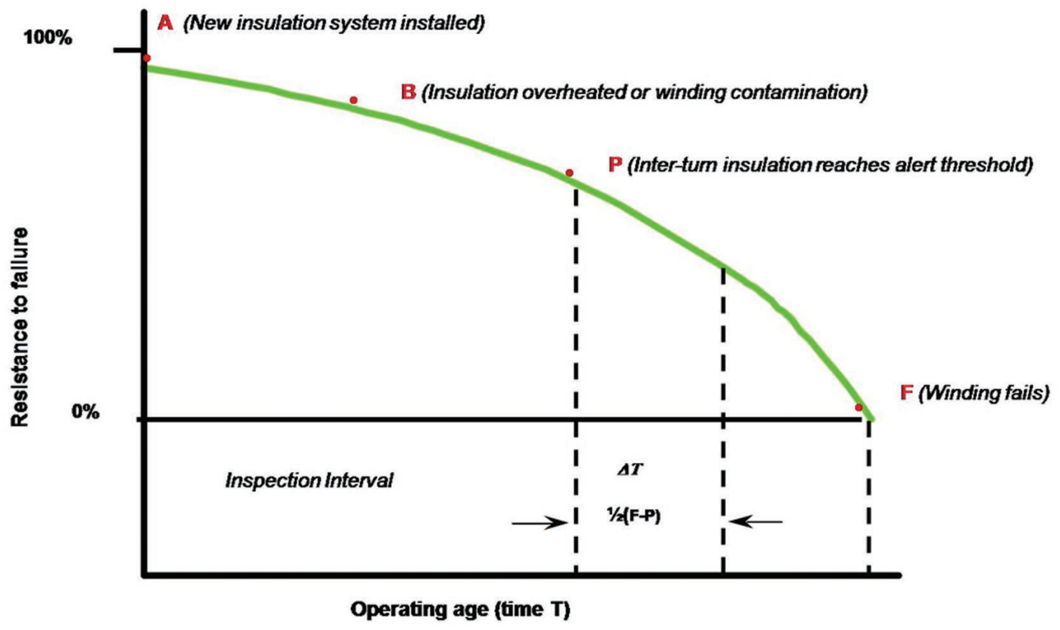

Figure 3. Failure curve of Primary A for bearing detection scenario.

In the next scenario, we use the alternating pump system (Primary A and B) and perform inspections and testing on the bearings and seals. We know that vibration should be performed every six weeks in order to detect bearing failure and a monthly seal inspection in which a slight leak indicates failure in 2 months. In the above scenarios, the bearing in Primary A shows a signature with a slope of 0.02 with a result of D = 0.98 and the MTTF of 1440 hours (12 weeks times 120 hours). At that point, the Primary B has an availability of 0.76 or 76% while Primary A is now on a new time-clock with an availability curve as shown in Figure 2. With this information, a decision can be made as to the optimal time to perform corrective maintenance which will have a minimal impact on the availability of the system.

Testing Frequency for TTFE

In order for a TTFE condition-based maintenance program to work, the testing and inspection has to be performed at a frequency that is able to detect the fault(s) that you are looking for in advance of failure. The frequency of testing and inspection depends upon the severity of the fault, operating conditions, equipment design, and operating environment with inspections and tests designed to detect those faults.

As shown in Figure 3, the minimum frequency of testing and inspection for TTFE is 1/2 of the point at which the test or inspection can identify the fault, or the alarms are set, to the point at which the equipment functionally fails. Functional failure is the point selected by the equipment owner that the equipment has too low a resistance to failure, the equipment ceases to meet its required operation, or the equipment ceases to operate [10].

For instance, if insulation degradation causes a change in polarization index readings an average of 2 months prior to equipment failure, then the frequency of test should be one month. The average time to failure should be adjusted based upon the criticality of the equipment and the availability of repair or replacement.

Conclusion

The purpose of the TTFE technique is to provide a tool for engineers and technicians for risk-based reporting of condition-based maintenance tests and inspections. Through the proper application of this technique, corrective action may be prioritized improving the effectiveness of the maintenance program. Instead of stakeholders being required to make decisions based upon experience only, equipment, failure, and repair history can be used to enhance the process, improving the availability of critical equipment.

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