CONDITION BASED MAINTENANCE

by

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1.0 . . . . ABSTRACT

Like all other efforts which require the expenditure of funds, electrical maintenance is changing. Competition, costs, and equipment complexity have increased while budgets, operating margins, and maintenance staffs have decreased. As never before, the maintenance department must be able to show a positive effect on the "bottom line."

Condition Based Maintenance (CBM) offers the promise of enhancing the effectiveness of maintenance programs in a way that no other single concept has ever matched. This relatively new approach to maintenance uses data drawn during operations and/or maintenance intervals to forecast the need for additional or future maintenance. It extends the concepts of predictive maintenance by using data from both on-line and off-line maintenance tests.

This paper

reviews the classical approaches to maintenance and then compares and contrasts them with CBM. A variety of factors which affect the selection and performance of various maintenance alternatives are presented followed by an overview of the concepts and procedures involved in CBM. The intent is to allow readers to analyze the benefit(s) that the technique might have on their maintenance program.

This paper was presented originally at the 1993 AVO Technical Conference. In 1994 a new section (6.0) was added to describe some of the changes and events that had occurred since the original presentation. In addition to general updates, subsequent revisions have added descriptions of the analytical techniques that are being used or researched by companies which have adopted CBM. Sufficient detail is provided on the more promising mathematical techniques so that the reader may evaluate them for application to specific power systems.

2.1 Breakdown Maintenance or Repair

Some would object to including this section as a maintenance concept. However, even today, many companies *choose* to “run it until it breaks”. All too often we hear statements such as “We can't take that out of service.” or “We've never had a problem so why bother to perform maintenance.” Such an approach gambles that when a failure occurs, the resulting outage and repair costs will be less than the investment required for a preventive maintenance program. Surprisingly, breakdown maintenance does employ minimal preventive maintenance techniques. Lubricant levels, bearing and winding temperatures, load currents, voltages, power factors, and other such easily obtained data are measured; however, action is taken only when urgently and immediately required. Table 1 lists some of the more common data items and how they are used in a breakdown maintenance approach. Notice that breakdown maintenance may not involve any data point analysis at all.

Data Point	How Used
Load Current	Transformer or other equipment replaced at first outage.
Voltage	Tap changers adjusted if available.
Lube Oil Level	Lube oil added as necessary
Temperature	Symptomatic treatment such as checking cooling systems or adding fans.

Table **1**. Data Handling in “Breakdown Maintenance”

Breakdown maintenance will be cost effective so long as no catastrophic failures occur. Of course, such an approach leaves the system open to major catastrophes because no precautions are taken to prevent them. This means that extremely hazardous conditions can exist with no way to predict them.

Sadly, breakdown maintenance is the approach still used by far too many companies. The economic pressures mentioned earlier force organizations into a mistaken belief that running it until it breaks is the cost effective approach.

2.2 Preventive Maintenance

Preventive maintenance (PM) is currently the most widely accepted approach to maintaining electrical equipment. PM is a calendar based program in which very comprehensive test routines are applied to off-line equipment. Comprehensive test methods such as insulation resistance, power factor, protective device calibration checks, and circuit breaker time travel analysis, are used to evaluate current system conditions. Table 2 illustrates some typical data and briefly describes how they are used in the implementation of a preventive maintenance program.

Data Point	How Used
Insulation Resistance	**Values are spot checked against industry norms. “Bad” insulation is replaced immediately. “Questionable insulation is scheduled for re-test.**
Insulation Power Factor	**Treated in a manner similar to insulation resistance.**
Protective Device Set Points	**Devices are adjusted to meet calibration settings provided by engineers. Equipment is also cleaned and adjusted mechancially.**
Circuit Breaker Time/Travel Analysis	**Breakers are adjusted to manufacturer’s specifications.**

Table **2** - Data Handling in Preventive Maintenance

There are two very significant differences between the way the data are used in breakdown maintenance programs and preventive maintenance programs. In a PM program:

- Data are collected during both on-line and off-line times. Off-line times are intentionally scheduled for the implementation of preventive maintenance procedures.
- Equipment which is discovered to need repair will be scheduled for outages to implement those repairs.

The principle problems with preventive maintenance programs are found in the financial department. Like life insurance, preventive maintenance programs cannot be economically evaluated except statistically. Consider a conversation that was overheard and reported by a student several years ago:

Maintenance Supervisor:	*"But boss, statistics show that companies with a good preventive maintenance program have 30% fewer unplanned outages."*
Boss:	*"But ... we have never had any unplanned outages."*

Preventive maintenance returns cannot be measured—unless an unplanned and/or catastrophic outage occurs. When such an outage occurs, the value of a maintenance program can be compared directly to the cost of the outage. Such thinking is too philosophical for many financial officers, and so, preventive maintenance programs have an uphill battle all the way.

In spite of this difficulty, PM programs have become increasingly more common since the early 1950s. The widespread, good results have become too apparent to be ignored by all but the most stubborn. Insurance carrier requirements are also moving many towards PM.

2.3 Predictive Maintenance

Predictive Maintenance takes advantage of proven **cause↔symptom↔effect** relationships to *predict* the need for corrective action. Consider dissolved gas analysis, for example. Industry experience has established limits for the amount and rate of change for combustible gases in insulating oil. Based on extensive analyses, we know that arcing is undoubtedly present in a transformer if the amount of acetylene rises above a certain concentration, or if its rate of production increases beyond a certain value. Thus if analysis shows that acetylene has exceeded these amounts, we can safely *predict* that arcing is occurring. Further, we can often predict how long the transformer has until failure. The transformer can be immediately scheduled for an outage, the cause can be isolated, and a repair can be implemented.

Predictive maintenance is generally an equipment specific type of approach rather than a system wide strategy. That is, most facilities do not use predictive techniques throughout their system. Rather they will use equipment or specialty vendors to perform predictive procedures on their motors or transformers. Infrared scan is one of the few procedures that is performed on a system wide basis.

Table 3 shows three of the most common types of predictive maintenance procedures employed in modern power systems. Please note that the descriptions given are in no way intended to be rigorous.

Data Point	How Used
Motor Vibration	Vibration values are compared against manufacturer or industry supplied norms. Motors with vibration signatures which exceed these norms are scheduled for off-line repair.
Dissolved Gas Content	Gas content and percentage increase are compared to industry norms. Equipment which exceed these norms are scheduled for off-line repair.
Thermographic Scan Temperatures	Temperature rise is compared to industry norms. Equipment which exceed these norms are scheduled for off-line repair.

Table **3** -Data Handling in Predictive Maintenance

Rather they supply general knowledge as to how such programs work. The steps in a predictive maintenance program can be summarized as follows:

1. Key values are observed or measured.
2. These values are compared to norms for the equipment and potential problems are predicted.
3. Any equipment which falls outside of norms is scheduled for repair or re-testing.

Predictive maintenance methods are often incorporated into a preventive maintenance program. No outage occurs, repairs are scheduled, and major failures are averted. Predictive maintenance offers a very cost attractive maintenance alternative.

2.4 Condition Based Maintenance

Condition based maintenance (CBM) has many similarities to predictive maintenance in that the data gathered during CBM intervals are compared to statistical norms—both averages and trends. CBM is more comprehensive than predictive maintenance since it uses both on-line and off-line test data. The principle benefit of CBM, however, is the manner in which data is used. Table 4 illustrates these principles. Test data is analyzed and future maintenance procedures on the equipment are determined by the results. The most significant difference between CBM and other types of maintenance is found in the first column of Table 4. If the equipment is in execeptionally good condition as indicated by the test results—***THE NEXT SCHEDULED MAINTENANCE MAY BE SKIPPED ALTOGETHER FOR THIS EQUIPMENT!!***

Results Within Norms	Moderate Deviation	Severe Deviation
Minimum or no interim service inspections. COMPLETELY SKIP THE NEXT SCHEDULED MAINTENANCE	Perform more in-depth procedures during this interval. Include as usual in next maintenance interval.	Schedule interim tests before next routine maintenance interval Remove equipment from service for disassembly and/or rebuild

Table **4** - Condition Based Maintenance Procedures

Since only a relatively small percentage of system equipment will exhibit problem test results at any one interval, it is reasonable to expect the overall maintenance effort to reduce drastically—perhaps to as little as twenty percent (20%) of pre-CBM levels. Such reductions are possible because only that equipment which is shown, by test data, to need additional servicing would be “on the list” for the next maintenance interval. Equipment that has been tested once every two years may now need attention only every five to ten years.

3.0 . . . . CONTEMPORARY MAINTENANCE INFLUENCES

3.1 Economic

At least one statement is true regardless of the time period in which it is made, “The cost of business is increasing.” Equipment replacement costs are increasing, labor costs are increasing, unscheduled downtime costs are increasing, insurance costs are increasing—in fact, just about every cost that can be imagined is increasing.

The rising competition from the international community adds to this upward spiral. Companies which used to compete locally, must now compete internationally. Industrial companies, electrical utilities, commercial ventures, and government agencies must all improve their efficiency and reduce costs in order to remain competitive and economically viable.

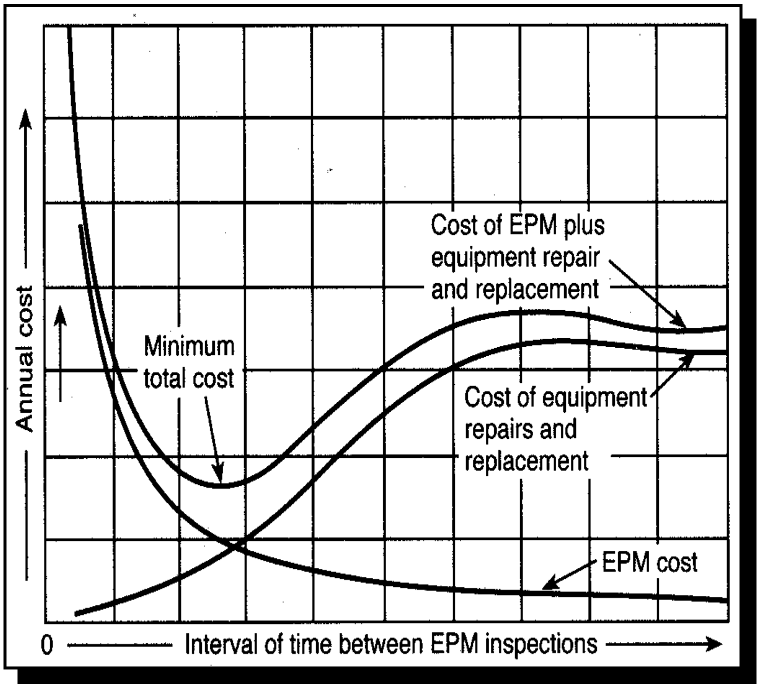

Figure 1 - Effect of electrical maintenance on annual costs

Figure 1 shows the effect that a good electrical preventive maintenance program can have on the overall cost of doing business. The concepts shown in this diagram have been known for many years and have been published in a variety of industry standards. As the time between maintenance intervals increases, the cost of the maintenance goes down. This is intuitive since the amount of maintenance decreases when intervals increase.

In contrast, the cost of equipment repair and replacement increases because of the additional outages and problems which result when the equipment is not properly maintained.

The total annual cost is quite high at either end of the maintenance interval range. That is to say, if too much maintenance is performed the total costs are high because of the high cost of maintenance. If too little maintenance is performed total costs are high because of the additional expense of equipment repairs and replacement.

The optimum selection for the amount of maintenance is that which provides the minimum total cost. CBM can greatly effect this curve. When CBM is employed, the effectiveness of the maintenance that is performed increases greatly. This means that the increased repair and replacement costs will not rise so quickly when the maintenance intervals are increased; thus, the minimum cost will be even lower.

3.2 Technological

Technology is helping reduce the costs of maintenance efforts in two major areas. First is the improvement in test equipment. Modern test sets are available which can greatly increase the speed of performing test procedures. Many of these test sets allow data collection either by computer or with their own built in intelligence. Communications ports are provided in some equipment so that stored results can be sent to a printer or to a computer for storage, manipulation, and later retrieval.

The personal computer is providing the second great technological boost in the collection and analysis of test data. Test equipment that can be interfaced or even controlled by computer allows test technicians to generate meaningful, consistent results in much less time that previous methods. Gradually, maintenance is moving into the computer era. Computers can operate test equipment, create automated test reports, analyze data and flag problem areas, help to evaluate the need for further maintenance procedures, upload data to the master maintenance management program, and provide many other such services.

3.3 Equipment Aging

All things age and power equipment is no exception. As the system equipment ages it becomes increasingly prone to unexpected failure. In contrast, equipment that is properly maintained is much less likely to fail—even when it is old.

As equipment ages it becomes harder to maintain for two significant reasons. First, parts are very difficult to obtain for old equipment, especially if the manufacturer has stopped supporting it.

Conversely (or perhaps perversely), equipment that has been over-maintained may literally be worn out. Consider protective relays for example. In many cases we wear them out by testing them. Protective relays operate in service for perhaps ten seconds in their total lifetime —say forty years or so. If the relay is tested every year and is energized for thirty seconds during each testing interval, it will operate under test for 1200 seconds. In other words the relay will be operated under test for 120 times as long as it is expected to operate when it is in service.

3.4 Modern Technology Power Equipment

Interestingly, new equipment may also prove to be a maintenance problem. Twenty years ago, equipment was mechanical and relatively “low tech.” Modern power equipment often is much more sophisticated. Variable speed drives, UPS systems, circuit breakers with CPUs, and computerized protective relays have brought line equipment into the high technology age. Maintenance programs are complicated by the need to train personnel in the techniques required for such high tech equipment.

3.5 Personnel Retirement/Downsizing

Ailing budgets find it difficult to replace retired or downsized personnel. In addition to the replacement costs, the expertise that these employees had is gone. Even if new, quality personnel can be hired, they will not have the years of system knowledge of the retirees. Worse, new employees may not be available who know how to maintain some of the older systems that are still in use. Companies may find it increasingly necessary to utilize consultants and contractors.

CBM can help in this situation by reducing the amount of maintenance required. Equipment that is only maintained when it needs to be will not require as intensive a maintenance program.

4.0 . . . . CONDITION BASED MAINTENANCE -- AN OVERVIEW

4.1 What is Condition Based Maintenance

CBM is a modern procedure which uses the condition of equipment to determine what, if any, testing and maintenance procedures should be performed. CBM is similar to a preventive maintenance program which includes an extensive array of predictive maintenance procedures. Note however, that predictive maintenance tends to be equipment oriented while CBM is system oriented.

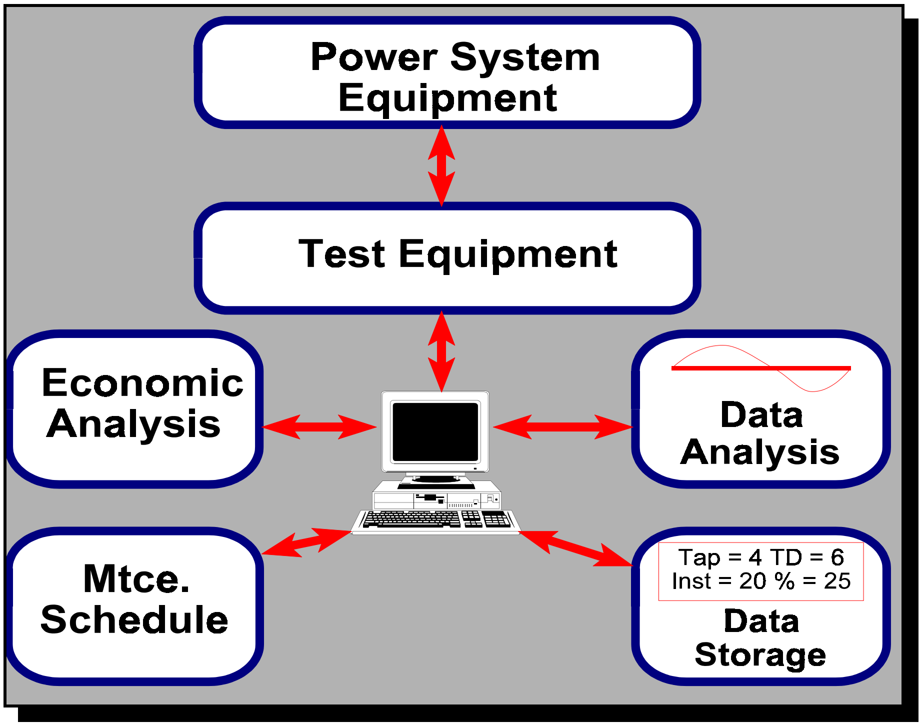

Figure 2 - Typical CBM data structure

Equipment is maintained as usual including all normal tests as well as visual mechanical adjustments and inspections. Both on-line and off-line procedures are performed and test data are collected into a computerized data base. The test technician uses a notebook computer for this purpose. The data may be loaded by keyboard, or in some cases the test equipment will store the data directly.

The test results are initially reviewed by the technician performing the work. This review may be via statistical analysis software and/or by simple inspection and comparison. After the initial review, the data is uploaded to a central computer, where it is subjected to a more extensive review.

The statistical analysis comprises two sections—statistical averaging/comparison and trending. Table 5 describes the two methods and illustrates how they are used.

Note that CBM relies heavily on the computer. Data collection, analysis, and storage; project tracking and scheduling, and report generation are the key elements which depend on the computer. Figure 2 is a block diagram of an equipment setup that is ideal for a CBM program.

Statistical Procedure	Description and Evaluation
Averaging and Comparison	Test data are compared to previous tests and other equipment of the same type. Equipment with results that deviate more than the specified amount are set up for additional procedures
Trending	Changes from previous tests are analyzed. If the trend exceeds specified amounts, the equipment is set up for additional procedures

Equipment that is within normal tolerances may be bypassed for one or more subsequent maintenance intervals.

Table **5** - Statistical analysis techniques for CBM

4.2 The Effects of Condition Based Maintenance

The use of a CBM program will blend perfectly with the five factors mentioned in section 3. Using a properly applied CBM program companies will increase the overall effectiveness of the maintenance program while decreasing overall costs. These are important considerations when evaluating a CBM system.

4.3 Required Equipment

Test equipment, computers, and software are the principle requirements for the implementation of a CBM system. Existing test equipment is sufficient for starting the CBM program; however, upgrading to modern units which will readily interface with computers is strongly recommended.

Notebook or laptop computers should be available for field test personnel. These will replace the pencil and paper approach to filling out test forms. Some existing test software has the ability to automatically save test results on disk; however, much improvement in these areas is expected in the next few years.

Influencing Factor	Effects of CBM
Economic	Reduces overall cost of maintenance by reducing the intensity required to achieve results.
Technology	Use of modern tools—test equipment, computers, software— speeds the process.
Equipment aging	CBM can reduce the amount of maintenance required, and therefore reduce the amount of wear and tear caused by frequent testing. Since CBM focuses on condition rather than time, even older equipment will be made more reliable.
Modern Technology Power Equipment	CBM puts emphasis on performance of equipment as opposed to internal workings. This means that maintenance personnel can spend more time evaluating operation without worrying about the internal operation of high tech equipment
Personnel Retirement	Increased maintenance intervals makes it easier to support maintenance with decreased staff size. Also, increased intervals means increased training times. Finally, companies may more comfortably, and economically, depend on outside contractors for maintenance work.

Table **6** - Effects of CBM on various influencing factors

5.0 SUMMARY AND ANALYSIS

Although CBM is new it shows great promise as the maintenance technique of the future. Some companies are developing programs which have rudimentary CBM concepts. Partnering arrangements are being developed which should implement some of the first system wide CBM programs. These programs promise to provide a level of maintenance service which exceeds any based on more conventional technology. Table 7 lists the principle advantages which users of CBM can reasonably expect to realize.

Benefit	Explanation
Familiar Procedures	The test and maintenance methods that have been used in the past will work equally well with CBM. Test results are saved and analyzed statistically and used as the basis for additional procedures.
Minimum Effort	As the program continues, only that equipment which needs to be maintained is maintained. This means that equipment which tests within its normal values does not have to be scheduled for additional work. In fact, it can often be skipped altogether.
Cost Savings	Some estimates indicate potential reductions in maintenance manhours by as much as 50%. The cost of additional equipment and software should afftect this only minimally.

Table **7** - Expected benefits of a CBM program

6.0 . . . . CBM STATISTICAL ANALYSIS

6.1 Introduction

The purpose of statistical analysis of CBM data is to detect indications of change in electrical system performance well in advance of any system malfunction. This requires that mathematical models of "normal" system performance be developed so that condition assessments can be made. Existing data from an aggregate of specific components and similar systems are used to establish the general patterns of variation that may be expected when collecting data, over time, on a given parameter. Once that parameter has been modeled, each newly collected data point may be compared to that model to determine system condition, and appropriate action may then be taken.

6.2 Characteristics of CBM Data

Data collected from maintenance surveys have some specific characteristics. For each measured parameter, only one test measurement is made; these measurements are component or system specific. Measurements are made infrequently with test cycle times ranging from several weeks to several years. Therefore, analysis must be made with only a small amount of data available from the specific system being analyzed. Fortunately, data from a specific system parameter tends to be relatively stable if the system is in good condition and proper environmental corrections are made (if required). For the purposes of this paper, CBM data is assumed to be normally distributed about an operating mean value.

6.3 Requirements for CBM Data Analysis Methods

The methods utilized for assessing CBM data must be sensitive to detecting significant change in individual measurements from the system model, as well as in the detection of trending or drifting of data accumulated over time. These methods must be relatively insensitive to minor random variations such as from the measurement system. CBM analysis must also provide a means for categorizing the level of performance of a device or system, so that decisions may be made as to the frequency of future inspections or the need for system adjustment or repair.

6.4 Application of Control Chart Strategies

Control charting strategies, based on the work of Dr. Walter Shewhart and expanded through the work of other statisticians, provide the means for assessing collected test data against the predicted performance of an established model. Control limits are calculated from known or estimated system variation and performance bands are defined in increments of standard deviation from the nominal operating level (average). Figure 3 shows the general design of a control chart which has a central line positioned at the average level of any measured parameter and increments of standard deviation--which is a measure of variation--on either side of the central line.

Statistical theory and extensive application indicate that when any operating system is in statistical control, repeat measurements will nearly always fall within 3 standard deviation (sigma, **σ**) either side of the central line on a control chart, with data more likely to fall near the center of the chart than toward the extremes. This theory applied to CBM test data provides a means for statistically assessing the condition of the test system.

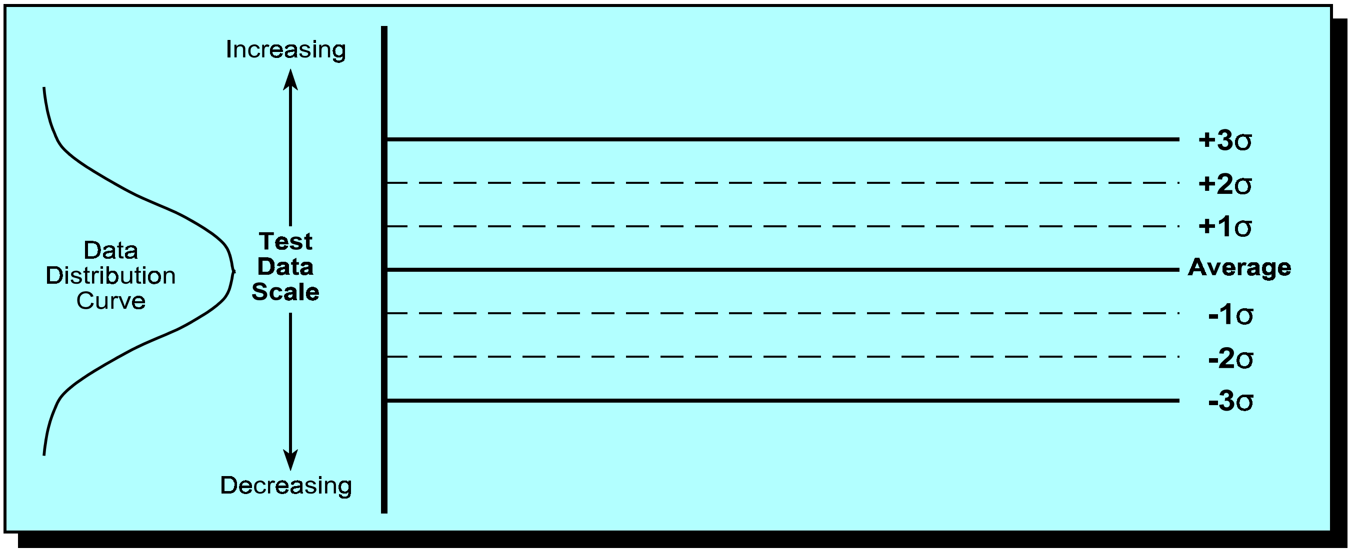

Figure 3 - General control chart design

6.5 Evaluation Criteria

Having modeled the control charts from known or expected levels of system performance, several levels of action may be taken as a result of where a test data point falls on the chart. For example:

- If the test reading is within ±1 sigma of the central line, system performance is categorized as "Excellent", assuming there are no extenuating environmental concerns noted during system inspection and no visual degradation of the physical system. As a result, the next inspection of that parameter may be skipped with high confidence that component or system performance will not be adversely affected.
- If the test data point falls between ±1**σ** and ±2**σ,** visual inspection of the physical system and environment is acceptable, system performance is deemed stable and the normal testing interval is maintained.

- "Caution" levels are defined by the area between the 2σ and 3σ boundaries. If test data falls within the caution area, or visual inspections revealing noticeable deterioration, the CBM test frequency should be increased.
- Any data point falling outside of the 3 sigma boundaries indicates that the operating system being measured has significantly changed. In this instance, or if the test reading is approaching established industry limits, a plan for mitigating action should be developed. This action might require an adjustment to the system or could indicate that an estimate of potential useful life of the component or system being measured should be made. Provisions for component replacement may be scheduled in advance of system failure.
- Should the CBM test reading be well beyond the control chart 3 sigma boundaries or outside of established industry limits, a system fault has been detected and immediate repair or replacement of affected components is required.

6.6 Types of Control Charts Utilized

Three types of control charts may be employed in the evaluation of CBM data. The first is the Individual X-Moving Range chart (Figure 4 & 5) which is a combination of two charts. The Individual X chart is essentially a trend chart of the collected test readings over time. This chart is used to test the significance of variation noted in each individual test reading. The Moving Range chart assesses the significance of change between consecutive test data points for each measured parameter by plotting the difference between the last two measurements at each test cycle. Exceeding the control limits of this chart indicates that excessive variability is present in the test system and action should be taken to determine its source.

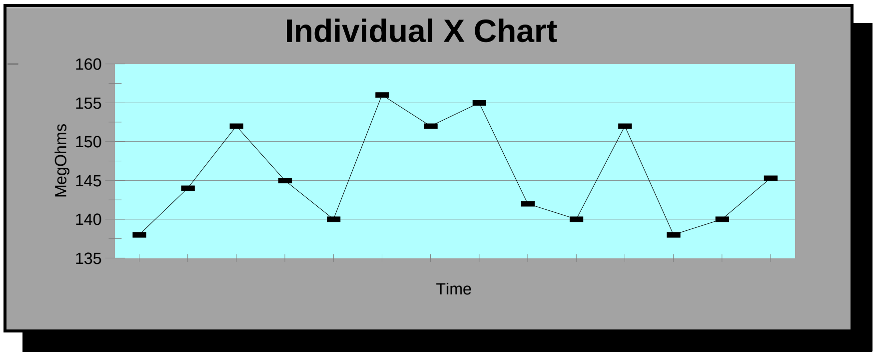

Figure 4 – Individual X chart

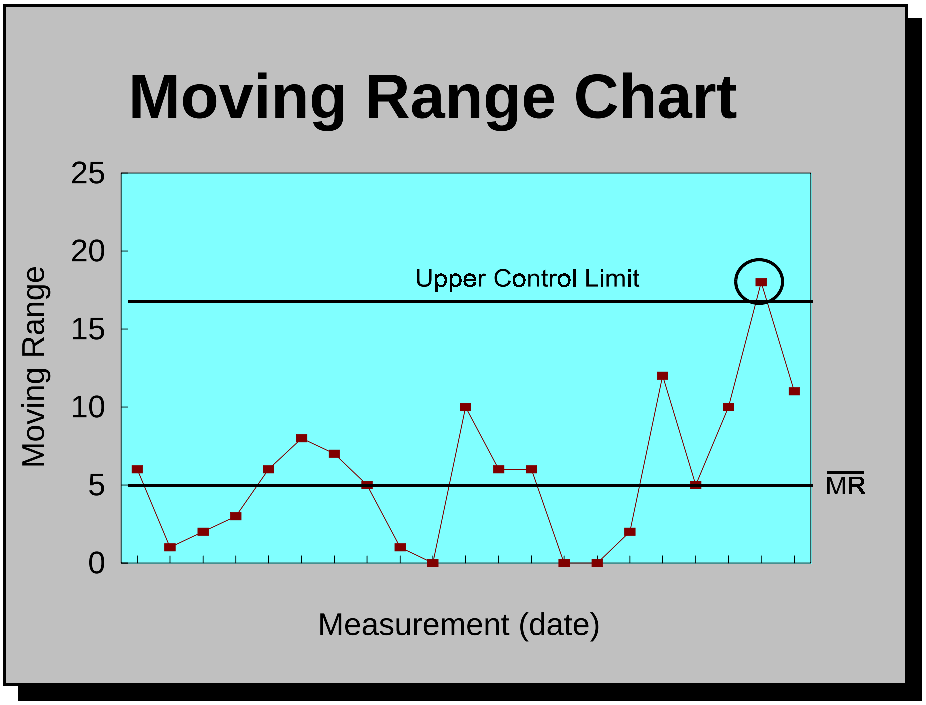

Figure 5 - Moving Range Chart

The second type of control chart used in CBM analysis is the Cumulative Sum, or CUSUM chart (Figure 6). By sequentially summing the differences between the test data value and the operating average value of the system over time (S_i)

where:

$$\boxed{S_i = (x_i - \mu_0) + S_{i-1}} \quad \textbf{(1)}$$

The CUSUM chart is an effective method for detecting significant trending or drifting—an indication of system degradation.

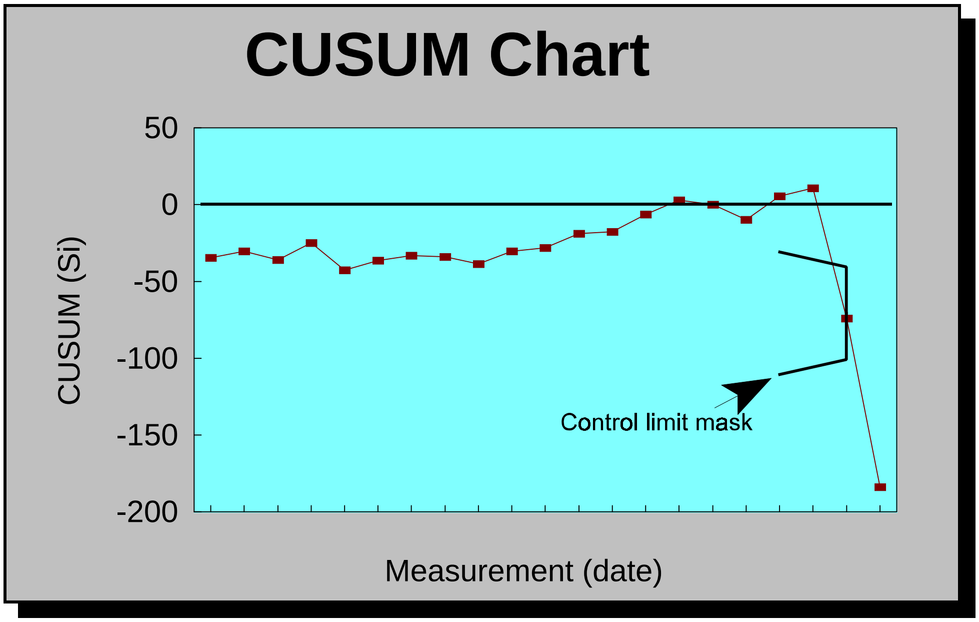

Figure 6 - CUSUM Chart

The Exponentially Weighted Moving Average chart (Figure 7) is the third control chart method used in CBM data analysis. This chart also seeks to detect drifting or trending, but it is different from the CUSUM chart in that it more heavily weights the affect of more recent data. This allows for detection of increased rates of system degradation.

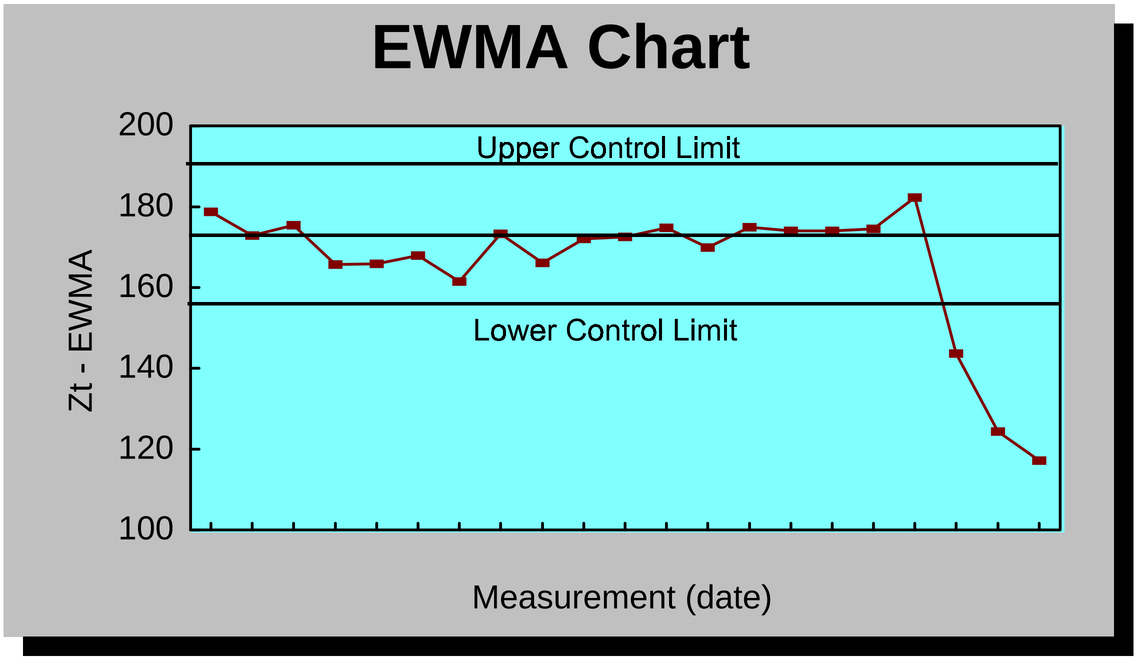

Figure 7 – Exponentially weighted moving average chart

$$\boxed{Z_t = \lambda \overline{X}_t + (1-\lambda) Z_{t-1} \quad Where \quad 0 < \lambda \le 1}$$

Using all three charting systems is more powerful that using any one method, as each approach is designed to detect system variation in a different manner. Exceeding control limit boundaries on any one of these charts is cause for system assessment and/or corrective action to be taken.

6.7 Conclusion

Even though each of the control chart methods described in this paper are proven techniques, their application to CBM is in its infancy. Preliminary results indicate that using a statistical approach to maintenance data analysis promises to be a more effective method because it will not only detect potential system risk prior to failure and loss of that operating system, but also has the ability to extend system inspection times thus reducing maintenance effort and cost. Current research will be enhanced with an increase in the amount of available maintenance record data.

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