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Condition Based Maintenance
A White Paper Review of
CBM Analysis Techniques

High Technology Solutions for the Producers, Distributors and Users of Electric Power

Cadick Corporation

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Abstract

This paper supplies the reader with more complete knowledge so that more informed decisions can be made as to how an electrical maintenance program should be developed and enhanced. The paper starts by reviewing some basic concepts of **Reliability Centered Maintenance (RCM)** with particular attention paid to its subset: **Condition Based Maintenance**. It then continues by showing the technical and financial advantages that **RCM** offers over classic **Preventive Maintenance** approaches. Finally, some of the current methods that are being used to mathematically model test results for the purpose of trending and life prediction are compared and contrasted.

Although these concepts can be applied to virtually any type of equipment maintenance, this paper focuses primarily on the maintenance of electrical equipment. Transformers, generators, motors, and power cables are examples of the types of equipment that can benefit from a **CBM** approach.

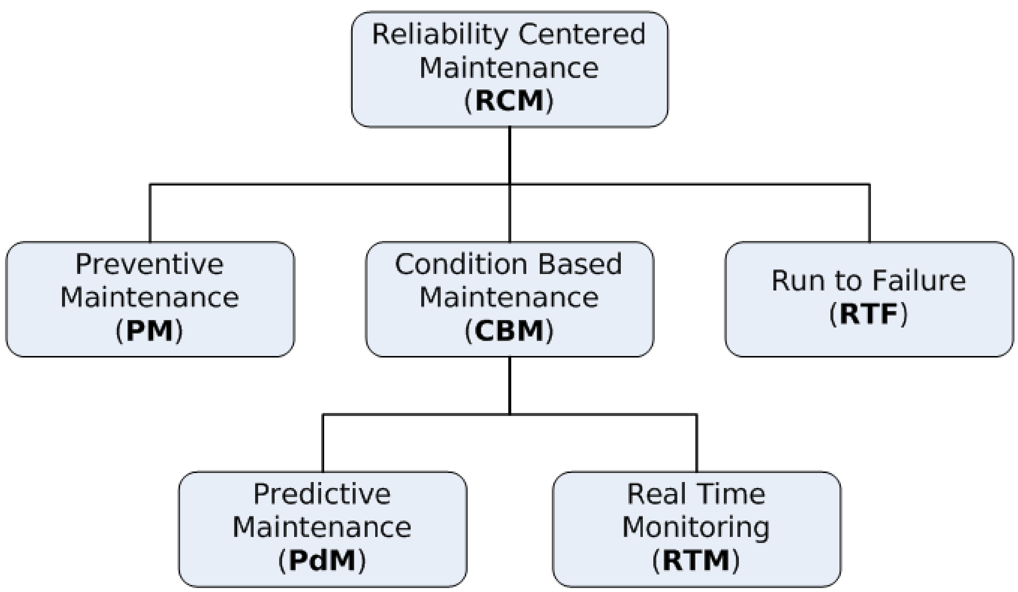

Figure 1 Simplified Block Diagram of Reliability Centered Maintenance

A basic block diagram of the **R**eliability **C**entered **M**aintenance (**RCM**) model is shown in Figure 1. **RCM** comprises three major elements – Preventive Maintenance (**PM**), **C**ondition **B**ased **M**aintenance (**CBM**), and **R**un **T**o **F**ailure (**RTF**). **CBM** is further divided in **Pr**e**d**ictive **M**aintenance (**PdM**) and **R**eal-**T**ime **M**onitoring (**RTM**). Although other models of **RCM** may be used, this relatively simple block diagram provides the basic structure required by this paper.

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The Elements of Reliability Centered Maintenance (RCM)

RCM is a holistic program that schedules and performs maintenance to optimize system reliability. Broadly speaking electrical equipment falls into maintenance categories as follows:

1. Equipment which is too inexpensive and/or non-critical to merit the cost of specialized maintenance attention. This type of equipment will normally fall into the **RTF** maintenance category.

2. Equipment which is expensive and/or very critical to system operations.
   a. For some such equipment the test results and/or operational parameters do not lend themselves readily to statistical analysis and trending. In this instance the equipment will be maintained using calendar-based (**PM**) methods.
   b. For equipment whose operational parameters and/or maintenance results can be analyzed statistically the **CBM** approach is employed.

The following sections provide a brief overview of each of these three maintenance approaches.

Run To Failure (RTF)

RTF is used for equipment that is non-critical, too small, and/or inexpensive to warrant maintenance expenditures. Small exhaust fans and light bulbs are among the types of equipment that usually fall into the **RTF** category. Electrical system operators must be very careful when employing *no-maintenance* techniques such as **RTF** since electrical failures can cause fires.

Preventive Maintenance (PM)

PM is a calendar-based maintenance system that is best suited for equipment such as circuit breakers and protective relays. The term *calendar-based* means that the equipment is tested on some periodic basis – annually for example.

This concept can be readily understood by a simple comparison. Car-owners know that lubricating oil should be changed every few thousand miles. The car manufacturer may specify that oil should be changed every 3000 miles or every 6 months, whichever comes first. Such a procedure is purely time (or mileage) based and does not take into consideration the condition of the lubricating oil.

A similar situation exists in the area of electrical equipment. Most companies perform periodic testing and maintenance on their protective relays.

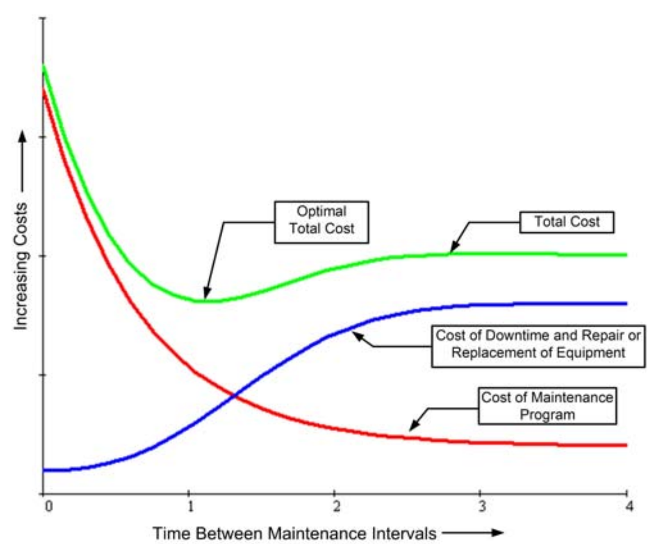

Figure 2 Costs vs maintenance intervals

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For example; overcurrent relay pickup, timing, and instantaneous settings are usually tested and “tweaked” annually, bi-annually, or on some other fixed, calendar interval. Since the results themselves may not be able to create a statistical trend, the calendar intervals are maintained because of the great importance of the relays.

Figure 2 is an industry-accepted graph adapted from NFPA 70B, *Recommended Practice for Electrical Equipment Maintenance*, 2006 Edition, Figure 4.2.6, Page 14. This graph shows the qualitative relationship between the frequency of **PM** and total costs. In general the desire of most **PM** programs should be to hit the *Optimal total cost* point as marked on the graph. Exceptions to this are found in industries where the hazards of equipment failure are too extreme. In these instances (the nuclear power industry is an example), the cost of **PM** is usually a secondary factor.

Another problem with the determining the cost/benefit ratio of **PM** is timing. Since **PM** has no prediction analysis, a change in downtime and repair costs will usually lag a change in maintenance intervals by up to several years. Increasing the maintenance intervals almost immediately decreases the overall cost. However, the negative results of that increase will not be seen until equipment replacement/repair and downtime later rises to erase any short term savings. As you will see further on in this paper, **CBM** techniques can virtually eliminate this problem since the analysis software is used to predict future trends on equipment condition.

Condition Based Maintenance (CBM)

In a **CBM** environment maintenance efforts and expenditures are based on the actual condition of the maintained equipment; that is, equipment that is consistently in good to superior condition does not need to be maintained as frequently as equipment that is deteriorating or has reached an age where deterioration is anticipated. The use of test or running data to statistically model and predict the future condition of the equipment is at the very heart of **CBM**.

Consider the oil change analogy mentioned earlier. If chemical tests on the lubricating oil predict that the oil has another 1000 miles of life – the owner can extend the oil change interval thereby reducing operating costs. Conversely oil that is tested to show rapid deterioration will be replaced ahead of time; consequently, **CBM** is much more cost effective than **PM** alone.

The Elements of Condition Based Maintenance (CBM)

Real Time Monitoring (RTM)

Real-Time Monitoring provides a continuous stream of data from operating equipment. For example, motor **RTM** packages have continuous monitoring of speed, vibration, voltage, current, and frequency data. Careful analysis of the collected data allows the user to diagnose incipient faults. An *incipient fault* is an impending failure than cannot be predicted by the normal senses including sight, sound, smell, and touch. The only way to diagnose an *incipient fault* is through advanced testing techniques.

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To be a valid candidate for **RTM** the equipment must satisfy two criteria:

1. The equipment must be critical or expensive enough to warrant the expenditures for the purchase and installation of the monitoring hardware and software.
2. Analysis of the monitored parameters (voltage, frequency, speed, etc) must provide meaningful equipment diagnostics and prognostics.

RTM is being used successfully on motors and generators. There are also transformer monitoring packages that show promise. However, not all equipment lends itself to **RTM**; moreover, there are a large variety of off-line tests that yield valuable, trendable results and may actually be less expensive than **RTM**. This is where **PdM** fits in.

Predictive Maintenance (PdM)

In its simplest form **PdM** uses test results taken from **PM** procedures. These results are statistically evaluated and a prognosis is developed allowing the system operators to increase, decrease, or even eliminate maintenance intervals. The ability to predict and thereby prevent failures is the true heart of **CBM**. In addition, when properly analyzed the test results can be used to provide a usable estimate of remaining equipment life.

CBM versus PM and RTF – An Overview

The following paragraphs compare and contrast **CBM**, **PM**, and **RTF** technically and economically. These comparisons are not exhaustive; rather, they provide the reader with key elements that should be included in any maintenance program structure decision.

Technical Comparison

Table 1 Technical Comparison of maintenance methods (See text for comments)

Approach	Specialized Tech Knowledge	Specialized Equipment	Extended Damages
RTF	Minimum	Minimal	Extensive
PM	Extensive	Moderate	Moderate
RTM	Moderate	Extensive	Minimum
PdM	Extensive	Moderate	Minimum

Table 1 shows a generalized comparison for the three components of an **RCM** approach. Note that **CBM** is divided into its two elements. The following outlined entries provide detailed explanations.

Specialized Tech Knowledge (Table 1)

1. **RTF** requires that service personnel be knowledgeable electricians. In this way, failed equipment can be safely and efficiently replaced.

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2. **PM** and **Pdm** require personnel who have an almost identical technical knowledge base These required skills start with, but go far beyond, the fundamental electrical knowledge required for all electricians and electrical technicians. The following list includes some of these necessary skills:
   a. Operation, adjustment, and troubleshooting of all the various types of electrical equipment that will be tested and maintained
   b. A firm understanding of power system technology and operations
   c. Training and experience in the use and application of many of the specialized test and monitoring instruments used. (A later section in this paper discusses some of these equipment types.)
   d. Complete training in the proper safety equipment and procedures to employ when performing the specialized test procedures.

   The one difference between **PM** and **Pdm** knowledge and skill requirements is in the use and interpretation of trending data. **PdM** personnel must have, at a minimum, the understanding to be able to review trending output reports and perform whatever additional functions may be required based on those reports.
3. Most **RTM** systems are installed with data analysis packages. In other words, the data is captured and analyzed automatically – often by computers. This means that the specialized knowledge required of **RTM** operations/maintenance personnel is limited to being able to interpret the software outputs and make decisions concerning needed actions. Generally speaking, once an incipient fault is predicted, electrical personnel can perform either replacement or repair as required.
4. In addition to the requirements discussed in 2a, 2b, 2c and 2d above, **PdM** personnel also require the ability to work with, interpret, and react to the output of the diagnostic procedures. In the ideal case, the ability to perform the required field tests and then later analyze the data results is found in one person. In some modern packages, such as *CBM 2010 (Pat. Pend.)* discussed later in this paper, the software itself can provide suggested actions for maintenance, repair, or replacement. In any event, this additional skill set adds little in the way of required training and skill beyond that already required for **PM**.

Specialized Equipment (Table 1)

Three types of specialized equipment are included in this entry.

1. Electrical test equipment
2. Monitoring and data communications equipment
3. Computer hardware and software to analyze test results.

Figures 3 through 7 show examples of this type of specialized equipment.

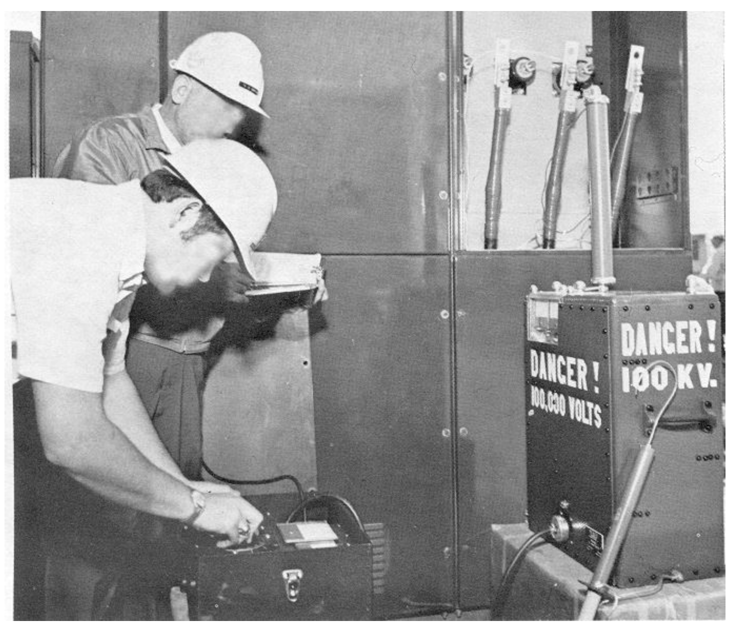

Figure 3 High potential test

Figure 3:

Figure 3 is a classic photograph of the use of a high-potential, direct-current test set. **(Note that there are safety violations in this Figure when modern standards are applied.)** This test set is often used to perform a *proof* test. That is, the test voltage is applied to the equipment, gradually stepped to a voltage that exceeds the insulation rated voltage by up to 300% or more, and left on for a specified time.

If the insulation does not fail the test is deemed to have *proved* that it will withstand the normal voltage. This so-called *go/no-go* type of test has fallen out of favor of many testing professionals and identified as a *destructive* test. However, when the test voltage is carefully and correctly applied in steps the results can be trended and used in a **PdM** program.

Figure 4 Megohm Meter

Figure 4:

Figure 4 is a photograph of a *megohm meter* commonly referred to as a *Megger*®.[1] This instrument is very similar to a high-potential test set with two significant differences:

1. The Megger® is usually has lower voltage and higher internal resistance instrument. Because of this – when properly used – the Megger® is less likely to cause unwanted damage to insulation, even when the insulation is in marginal condition. The Megger® is also usually much smaller and lighter than a high-potential test set.

2. A Megger® can be used in **Preventive Maintenance** (**PM**) for a *quick check* of insulation; however, its greatest value is realized when the test results are recorded and analyzed statistically in a **PdM** program.


Figure 5 RTM Equipment © Baker Instruments

For more detailed information on these two types of test sets and other commonly used insulation test sets go to the Cadick Corporation website at www.cadickcorp.com, click on the *Free Technical Information* button the left, and download Technical Bulletin *TB012b- Principles of Insulation Testing*.

Figure 5:

Figure 5 shows a Baker Instrument photograph of their EXP3000 instruments used for on-line monitoring (**RTM**) of electric motors. The EXP 3000 is used primarily for temporary test installations; however, instruments of this class can also be used for permanent installation and 24/7

[1] *Megger* is a registered trademark of Megger, Ltd.

monitoring. For example, Baker Instrument Company will soon be releasing a new system for the monitoring of electric rotating equipment. Based on the EXP3000 shown in Figure 5, the new system will monitor 41 parameters on 32 motors, up to 7 busses and is fully network capable.

These types of sets will monitor and report the motor operating parameters and will alarm when any parameter exceeds a preset level.

Figure 6:

In the early days of **CBM** most analysis programs were proprietary standalone applications run on a personal computer or embedded in test equipment. Recently newer and much more convenient delivery

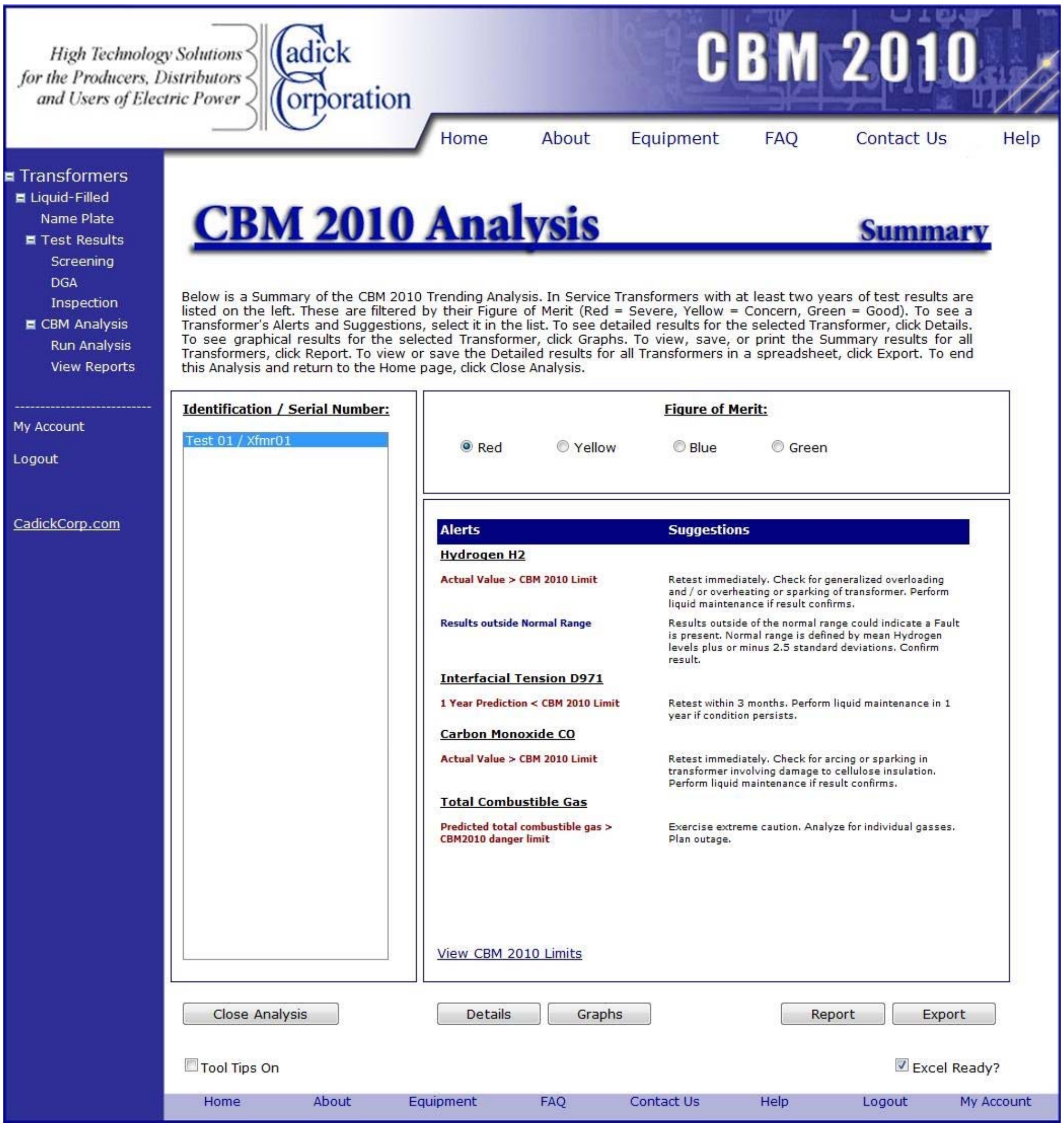

Figure 6 Screen capture of one page on the CBM 2010 *(Pat. Pend.)* website.

systems have been developed using subscription-based internet services. Figure 6 is one page of such a web-based application taken from the CBM 2010 *(Pat. Pend.)* website at http://www.cbm2010.com.

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This particular page shows a summary of results from the a dissolved gas test on a liquid filled transformer.

Figure 7:

This Figure shows a graphical output produced by CBM 2010 *(Pat. Pend.)* for the dielectric strength test of the insulating liquid (D 877). The bold blue line with test point dots show the actual test results for a period of several years. The blue, dashed line shows the software prediction for future results assuming that no physical maintenance is done on the transformer.

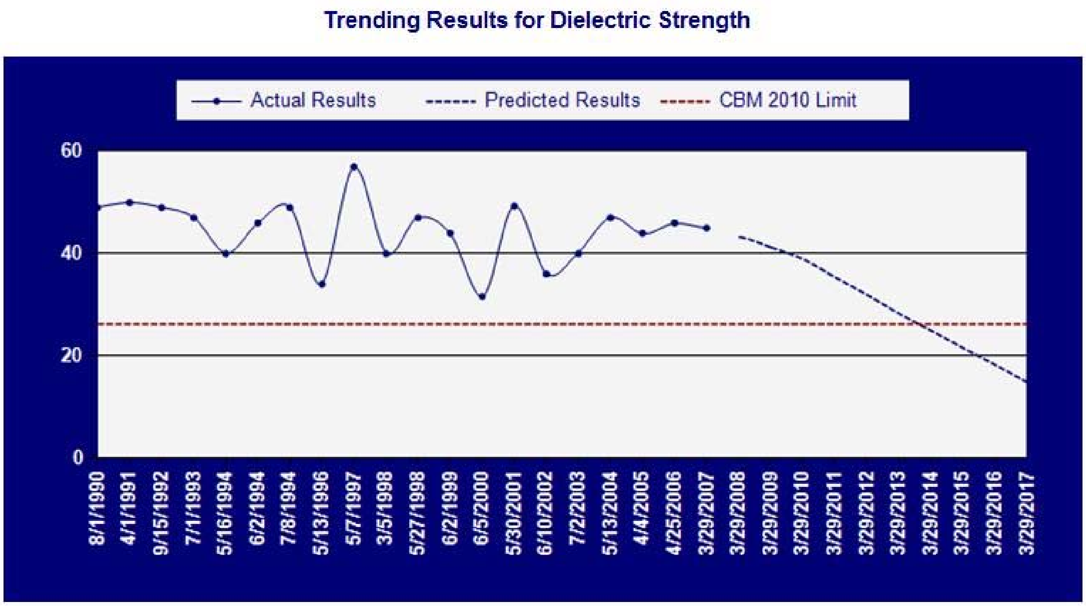

Figure 7 Test results and trending predictions for liquid insulation dielectric strength

Although much of the hardware, such as those devices shown in Figures 3 and 4, are common to both **PM** and **CBM**, the additional record keeping and analysis software does add slightly to the cost of the more advanced and useful **CBM** method.

Extended Damages (Table 1)

Extended damages include those failures of equipment caused by electrical equipment that are not maintained or are maintained too infrequently. (As will be pointed out later, maintaining equipment too frequently can also cause problems.) The philosophy of **RTF** will have the greatest number of such damages. Again referring to the automobile analogy, if the oil is never changed, the engine will fail much more quickly. If electrical equipment is installed and then left alone, it will eventually fail (probably sooner rather than later) for such reasons as lack of lubrication or faults that are not predicted.

Although the calendar-based **PM** will statistically reduce the number of undiagnosed failures, it is still subject to higher failures than **CBM** from four possible sources:

1. Excessive testing (test intervals that are too frequent) can stress equipment and cause it to fail early. This should not occur with **CBM** since the intervals are optimized.
2. Test intervals that are too far apart may allow equipment to fail because of an incipient fault that is not diagnosed in time. Again **CBM** reduces this problem by optimizing the maintenance and testing intervals.
3. Anytime that equipment is taken out of service, put into service, tested, or moved there is a statistical chance that it will be damaged in the process. Therefore when equipment is manipulated during a testing interval, the possibility of human induced failure is increased. This becomes much more significant when testing intervals are fixed and too close together.
4. Many failures that are predictable using **CBM** statistical analysis, will not show up on routine **PM** tests until it is too late.

Economic Comparison

The economics of maintenance systems will depend upon several variables. Some of the variables include:

1. The size, number, and complexity of electrical components in the given electrical system.
2. The effect that failure of a key component will have on the electrical and production systems for the particular plant or installation.
3. The level of investment that a company is willing to make in test equipment and monitoring systems.
4. The number of actual failures experienced.

The body of **PM** information gathered over the last sixty to seventy years has clearly shown that when **PM** is employed electrical system safety is increased, long-term operating costs are decreased, and equipment failure and downtime are decreased.

Somewhat more recent experience has shown that when predictive methods, such as those used in **CBM,** are added to the straight **PM** program even greater improvements occur. Moreover, overall costs are reduced by optimizing the maintenance intervals.

Table 2 shows the qualitative cost improvements that will be accrued as maintenance is moved from "None" to "Comprehensive."

Table 2 Cost improvements of maintenance programs

Type of Plan	**Relative Costs**	
	Short-term	Medium to Long-term
RTF only	Small	Very large
RTF plus PM	Moderate	Moderate
RTF, PM, and CBM	Slightly more than **RTF** + **PM**	Minimal

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The following bullets explain the key entries in Table 2:

- Since **RTF** requires no extra effort or specialized equipment, it has almost no short term costs associated with it. However as time passes, un-maintained equipment will start to fail. This can result in large, possibly catastrophic losses due to employee injuries, equipment repair or replacement, and/or loss of production. Of course, all maintenance programs have some small element of **RTF**.
- Adding **PM** to the mix introduces the cost of specialized test equipment, trained maintenance personnel and maintenance downtime. However, in the long term the addition of **PM** can greatly reduce the longer term costs by catching problems before they occur.
- The greatest savings are achieved when the predictive capabilities of **CBM** are added to the more traditional **PM** program.
    - The startup (short term) costs add a small amount as the necessary monitoring and/or analysis equipment and software is added to the necessary equipment base. These additional costs are minimal and often one-time.. The increased initial expense will be returned in decreased repair costs.
    - The long-term costs are often greatly decreased below the **PM** long term costs because the maintenance intervals may be increased and the failure rates will drop even more than with straight calendar-based **PM**.

Figure 2 on Page 3 was included to show the generally accepted relationship among the competing costs of a straight **PM** program. When a **PM** program is upgraded to include the elements of **CBM** the total costs are reduced in at least three significant ways:

1. The predictive methods used in **CBM** can predict incipient failures that a straight **PM** program will miss. This means that the *Cost of Downtime and Repair of Replacement of Equipment* curve will be lowered when **CBM** is employed. Over time, this reduction should more than offset any increases in spending for data collection and analysis.
2. **CBM** prognostications will allow the system owner to increase the intervals between maintenance tests for much if not most of the system electrical equipment. With the decreased frequency of maintenance the *Cost of Maintenance* curve will also be lowered.
3. Since **CBM** methods are most applicable to the "*big ticket*" items such as transformers, generators, motors, and cables, the improvements and overall cost savings are even greater than might be expected.

Data Analysis Methods for CBM

The basic methodology for **CBM** depends upon the collection of either operational data (**RTM**) and/or maintenance test results (**PdM**). With either **RTM** or **PdM** the collected data is then mathematically manipulated in one of several ways to determine the condition of the equipment and to develop a prediction of its future behavior. It should be noted that a properly written **PdM** analysis program is equally effective on data provided by **RTM** monitors.

The type of data collected, the sparsity of the data, how it is manipulated and trended, and how the information is delivered to the user are the major topics covered in the remainder of this paper. To begin, we will compare and contrast the differences between **RTM** and **PdM**.

Real Time Monitoring vs. Predictive Maintenance

RTM data is constantly delivered as long as the equipment is on-line and the test equipment connected; conversely, because **PdM** tests may be performed only once per year or less, the **PdM** data set is exceptionally sparse. This means that the statistical evaluation of **PdM** data must use methods that are effective for sparse data sets.

In spite of this challenge, **PdM** methods do offer one very significant advantage over **RTM**. Consider an insulation resistance test – normally performed on all types of insulation systems during both **PM** and **PdM** test intervals. Incipient insulation failures may only manifest as extremely small changes in current and resistance. In fact, changes of only a few milliamperes or milliohms may be the only precursors of an imminent failure. These changes are readily captured on quality **PdM** software.

On the other hand, since **RTM** data is collected during the actual operation of the equipment, these very small changes have to be captured from within the normal values of current and voltage. Normal values will usually exceed hundreds of volts or amperes. Although **RTM** technologies and mathematical models exist that allow this level of discrimination, results are much more readily obtained using the very precise measurements made using specialized, off-line test equipment.

The ideal way to provide accurate diagnosis of impending problems is to combine **RTM** and **PdM**. Each methodology is used in areas in which it offers clear advantage, data is collected, and predictions are made. The development of these predictions is frequently referred to as *trending*.

What is Trending and What Do We Expect from It?

Trending is the act of using past data values to predict future data values. Consider Figure 8, which shows an example of a simple, linear trending chart. Prior to 6/95, the resistance measurements for this equipment were all in the neighborhood of 10,000 megohms. Starting with the 12/95 test and continuing with the 6/96 test, the resistance values dropped significantly – indicating the possibility of an impending failure of the insulation.

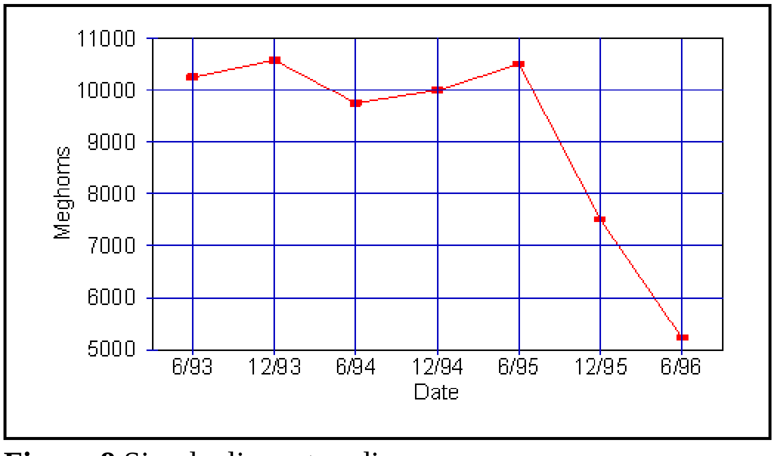

Figure 8 Simple, linear trending

The value of this graph becomes even more obvious when you consider the specific values of insulation resistance for the 12/95 and 6/96 tests. They were, respectively, 7500 megohms and 5200 megohms. When considered without looking at any previous values, both the 12/95 and the 6/96 values are well within the so-called *normal* range.

By comparing the last two data points with the previous values, you see that the insulation resistance has started a downward slide that points towards complete failure within one year. This is particularly significant in light of the fact that prior to the mid-1980s, records and graphs of this type were rarely

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kept. Rather, each reading was compared to an industry norm and given a *pass* or *fail* accordingly. Both the 12/95 and 6/96 readings would have passed using industry norms.

Although it represents a major improvement over norm-based systems, even simple linear trending is not the final answer. To understand this, consider Figure 9 which is a trending graph for parts-per-

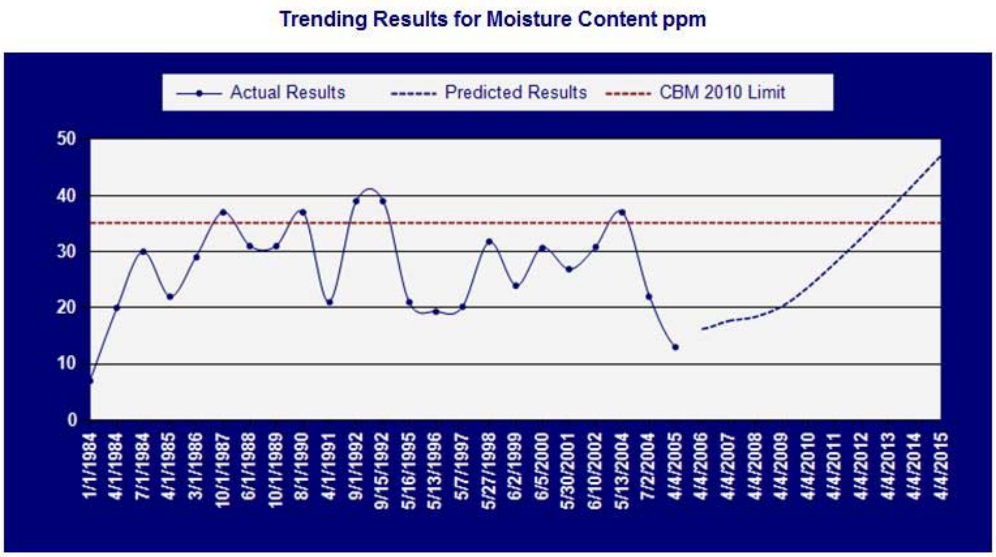

Figure 9 Results and trending for ppm moisture in transformer oil

million moisture in insulating oil. The data points on the dark blue line are the actual values measured over a period of years. Especially important in this graphs is the dashed, predicted results line. Note that it is quite non-intuitive. This is because the curve in Figure 9 was developed using very advanced CBM 2010 *(Pat. Pend.)* analysis algorithms. Such methods go far beyond a simple visual trend and show results that are not available using more fundamental approaches.

The following two points will clarify.

1. The trend line is counterintuitive. A visual analysis using simple trending would seem to predict a slow reduction in the ppm moisture. Although the specific mathematics are not available for this proprietary technique, it is clear that the more sophisticated analysis yields a result that is more severe than simple trending. The algorithms used have been vigorously tested and have shown that predictions are well within narrow statistical margins.
2. The last available data point for this measurement is from 2005. Although additional data points might modify the projection somewhat, rigorous testing of the algorithm has shown that over ninety percent (90%) of the predictions fall within one standard deviation out to three years beyond the last test.

This example shows that advanced trending methods can reveal useful results even from data that is not intuitively obvious like that shown in Figure 9.

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Using such advanced methods, the system operator can reasonably expect ample warning before major problems occur. A trend pattern that shows continued healthy predictions will allow the decision maker to extend the maintenance intervals – cutting the cost of the maintenance effort.

A trend pattern that indicates excessive deterioration or even failure can be used as the basis to schedule physical maintenance that will resolve the problem before it becomes an expensive outage and/or failure.

Fuzzy Logic

Increasing numbers of mathematical trending applications are using so-called *fuzzy logic*. The principles of fuzzy logic were developed by the mathematician Lotfi Zadeh in the mid-1960s. Fuzzy logic is sometimes flippantly referred to as the "life is in shades of gray" theory. That is, any given data point or trend may be neither *good* or *bad; that is,* 1or 0. Rather the data may be some value between 1 and 0. This allows the system to more accurately match the broad spectrum of *real world* values.

Fuzzy logic most often uses a set of queries instead of strict parameters for decision making. This makes the process attractive for control systems since it better resembles the way people make decisions. For example, an air conditioning unit has set parameters for when to turn on and off based on the feedback from a temperature sensor. When the temperature reaches, say 80º F the A/C unit will turn on and then turn off when the sensor once again reads the 79º F limit. A system implementing fuzzy logic could ask first if the temperature is rising quickly, then turn on the A/C to cool the temperature at a rate to counteract the quick rise. This allows for more control on the environment since it assumes, correctly, that the real world is not static but dynamic.

Artificial Neural Networks

In combination with fuzzy logic Artificial Neural Networks (ANN's) create an adaptive system for modeling system behaviors. ANN's use a non-linear approach to statistical data modeling. They are exceptionally useful in identifying patterns in non-sparse, high-volume data sets.

As the name implies, the behavior of an ANN is designed to mimic biological neural networks by creating complex relationships between the components, or nodes, in a system. Present day ANN's do not *self-learn* in the quite same way that artificial intelligence (AI) programs can. Rather ANN's use methodologies which strengthen (or weaken) the multitude of connections between nodes as more data becomes available. Thus these networks are always improving to better fit the control system it emulates.

Classic Rule-based (Algorithmic) Systems

A classic, rule-based approach is most useful when modeling systems that follow a clear pattern which can be quantified. An equation with set parameters, or rules, that can perfectly emulate a real world process is rare, to say the least; consequently, most classic algorithmic systems are created by compromise between the accuracy of trending results versus the number of variables defined.

The simplest algorithmic system contains only one variable. For trending purposes this is usually a linear equation over time where the rate of change is a set value. As variables are added the equation

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becomes less rigid and can allow for other factors such as age, environment, and usage. There are various approaches to defining these additional variables based on empirical data samples, including – but not limited to – maximum likelihood estimation, inferential statistics, and the method of moments.

Combinations of Fuzzy Logic, ANN Techniques, and Rule-based systems.

A more recent approach combines the older systems in a method that is especially applicable to sparse data sets. As an example, the previously discussed CBM 2010 *(Pat. Pend.)* system applies a combination of the multi-variate algorithmic approach and the artificial neural network's dynamic systems with self-training capabilities. While there are a set number of variables and relationships between them as in a rule-based system, the values of the variables are forever changing as in a self-training system like an ANN. Such an approach works well for sparse data sets in that each individual gains the benefit of the population for predicting future results. The impact of each individual on the population is based on the strength of the relationships so no one "rogue" unit can adversely effect the predictions of the others; a problem faced when trending most small data sets. As these data sets grow the relationships play a greater part in the trending. When properly developed the combined approach will work at least as well as ANN's for large data sets.

Data Delivery Schemes

Figure 10 Web based data input

As shown in Figure 10, virtually all data analysis systems use a computer at least for data input and output; however, all the complex mathematical systems in the world do not amount to much if the results are not easily available and understood. The three main delivery systems we will discuss here are

1. In-house developed spreadsheets using software such as MS Excel
2. Stand-alone commercial maintenance application software
3. Web-based commercial maintenance application software

1. Spreadsheets are best utilized with small data sets so the data can be quickly sorted and reviewed. Software programs such as MS Excel have the added benefit of easy-to-create charts and graphs to summarize the data to fit individual users' needs. Table 3 shows the spreadsheet with actual test data that was used to create the graph of Figure 8. Several inherent problems exist with this approach:
   a. As the data sets increase in size sorting and searching through spreadsheets becomes cumbersome.
   b. The probability of accidentally losing or corrupting the original results increases dramatically if a secure backup is not available
   c. Advanced trending techniques are not easily implemented in spreadsheets.
   d. In-house programming or expensive consultants are required
   e. All of the development costs accrue to the user.

2. Another option is stand-alone commercial maintenance application software. Such products often use an internal database that, after being populated by the user, can ensure data integrity from user error. Using pre-designed forms for input and output also lends to handling of larger data sets as searching and sorting is done automatically. Drawbacks include the following:
   a. Loss of reporting flexibility
   b. Limited to preformatted outputs
   c. Access limited to a single computer.
   d. To prevent loss of critical data, a disciplined system of local and off-site backups must be implemented.

Table 3 Insulation Resistance Measurements

Date	**Megohms**
06/1993	10,200
12/1993	10,600
06/1994	9,800
12/1994	10,000
06/1995	10,500
12/1995	7,500
06/1996	5,700

3. Web-based software, the third option, offers the same benefits of using standalone software without the limitations of access and security. The data is still stored in a database to ensure the integrity and the input and output is simplified with pre-designed forms. Security is a major priority on web servers so backups, virus protection, and firewalls are implemented with little to no user involvement.

   Another advantage of web-based systems such as CBM 2010 *(Pat. Pend.)* is the availability of a collective data set; thereby, allowing users the advantage of more robust trending and variable analysis. On the other hand, spreadsheets and standalone programs will only have access to a single user's data set for trending and predictions.

   While a web-based program does expand access to any computer that can connect to the internet, this usually comes with a service fee for the use of the site. However, this fee means never having to upgrade the software and includes the upkeep and security benefits. Comparatively, web-based systems give a user better access, security, and more advanced analysis while still maintaining an ease of use.

Summary

In this paper we have shown that **RTF** and **PM** are good solutions to **RCM** that save overall maintenance cost. **CBM** predictions added to **RTF** and **PM** further decreases cost and unplanned downtime. State-of-the-art analysis programs such as **CBM 2010** *(Pat. Pend.)* add yet another enhanced dimension to **RCM** at very little increased cost.

RTF is the no-maintenance technique. It is suitable for non-critical, low cost equipment that is easily replaced when it fails.

PM is calendar based scheduled maintenance. It is suitable for equipment such as circuit breakers and switchgear. Although **PM** reduces failures and down time, it usually results in non-optimal maintenance intervals.

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CBM currently consists of two elements, **RTM** and **PdM**. **RTM** can require expensive monitoring equipment. It monitors diagnostically meaningful parameters on expensive, mission critical equipment. However, not all mission critical equipment is adaptable to **RTM**.

PdM forecasts failures based on **RTM** data. **PdM** provides guidance allowing operators to change maintenance intervals to improve reliability.

RTF, **PM**, and **RTM/PdM** all have advantages and disadvantages. **RTF** has a low short term cost. But, undiagnosed failures and possible consequential damages may result in very high long term cost.

PM requires highly skilled personnel and special test equipment which can moderately increase short term costs. On the upside, a good **PM** program will provide a reduction in undiagnosed failures and lower long term overall cost. However, the **PM** interval must be correct in order to achieve optimal results.

RTM and **PdM** both have moderate short term costs. They require the highest level of skill and equipment but result in significantly reduced undiagnosed failures. The long-term reduction in cost is lower than **PM** alone.

However, **RTM** and **PdM** also have some shortcomings. **RTM** requires that the monitored equipment be online. **RTM** may have difficulty detecting the small changes that often predict future problems.

Until recently, most **PdM** procedures relied on simple linear trending. Although such an approach does represent a better approach than straight **PdM** it is not the final answer.

CBM 2010 *(Pat. Pend.)* is the latest state of the art advancement in **CBM** technology. It is a secure Web based application that provides analysis as well as maintaining a protected offsite backup of user data. With a web-connected computer, authorized personnel can access all the powerful aspects of the program. It provides superior prediction and data output flexibility when compared to in-house developed and stand-alone applications.

CBM 2010 *(Pat. Pend.)* utilizes advanced trending methods using Fuzzy Logic, Artificial Neural Network techniques, and Rule-based systems. With its large, collective data set results this program generates superior prediction accuracy. Over 90% of the resulting predictions are within one standard deviation for up to three years form the last test date.

Because of the prediction accuracy of **CBM 2010** *(Pat. Pend.)*, users can safely optimize **PM** intervals. This, coupled with judicious use of **RTF** for inexpensive ancillary equipment, will greatly reduce undiagnosed failures and provide the lowest-cost long term solution.

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