



Diagnostic Protocols for the Condition-Based Maintenance of High-Voltage Electrical Equipment

by

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Diagnostic Protocols for the Condition-Based Maintenance of High-Voltage Electrical Equipment

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Abstract

The diagnostic testing of insulation systems provides data that can be used to quantify the condition of high-voltage electrical equipment such as load tap changers, circuit breakers, regulators and transformers. Using recently developed algorithms, condition codes for these types of equipment can be generated using laboratory and field data. These codes are used to determine when maintenance is necessary and to prioritize maintenance activities. This paper describes how these condition codes are applied as the basis for a condition-based maintenance system. Case studies are included that illustrate the reliability and the fiscal impact of the protocols.

Introduction

Maintenance practices for high voltage electrical equipment are undergoing dramatic changes as utilities face the challenges presented by the specters of deregulation, privatization, mergers and acquisitions. Faced with reductions in workforce as well as reductions in budget, utilities are seeking alternatives to traditional time-based maintenance practices.

Historically, the establishment of time intervals for routine maintenance afforded a high degree of reliability albeit at a high cost. Extending the interval between maintenance operations could reduce costs, but this approach compromised equipment reliability. The Pacific Gas & Electric Company (PG&E) recognized the shortcomings of this approach and three years ago began to seek effective ways to introduce condition-based maintenance programs for its high-voltage electrical equipment. Working with TJ/H2b Analytical Services, PG&E cooperated in the development of condition-based diagnostic programs for both load-tap changers (LTCs) and oil-filled circuit breakers (OCBs). The companies are now extending the development of these programs to transformers and other types of oil-filled equipment.

These programs' protocols produce diagnostics containing condition codes and comments that are used to prioritize the equipment for maintenance. Maintenance is scheduled and performed on equipment that is in need of maintenance and deferred on other equipment. Savings are garnered from the deferred maintenance while the reliability of the electrical system is improved by focusing attention on equipment in the poorest condition. As an added benefit, these programs provide information that allows

for the safe handling of the insulating oil during maintenance and storage. This is achieved by determining the Safe Handling Limits(SHL) for the oil under test and comparing it to the actual level of dissolved combustible gases in the oil.[1 & 2]

Because the diagnostic information used for equipment assessment is derived from insulating fluid tests, information can be derived for all of the components in contact with the fluid. These programs, Breaker Oil Analysis (BOA™), Tapchanger Activity Signature Analysis (TASA™), and Transformer Condition Assessment (TCA™) each provide a specific equipment condition assessment based on the relationships of the components found in the fluid to one another and to the processes occurring in the equipment.

Although these condition-based maintenance programs were designed for utility implementation, they offer great value to service companies and industrial owners of high-voltage electrical equipment. Condition assessment enhances loss prevention, enhances maintenance planning and scheduling, and optimizes the maintenance activities that are performed allowing service companies to more efficiently provide and manage maintenance while allowing industrial clients to reap the benefits of higher reliability and better planning.

Development of the Methods

The discovery of an unusual failure mode in a model of circuit breaker found throughout the PG&E system led to an investigation to determine the possibility of applying condition-based maintenance practices to oil-filled circuit breakers. The need to identify troubled units prior to failure reinforced the desire to have reliable diagnostic tools to evaluate in-service OCBs. With this in mind, the study was undertaken to improve the diagnostic capability required to increase the safety and reliability of OCBs while decreasing the expense of costly internal inspection and maintenance procedures. To achieve this end, two goals were established:

1. Devise a non-intrusive means of estimating interrupter life, assuming normal wear.
2. Devise a non-intrusive means of identifying modes of failure.

In the first phase of the collaborative study between PG&E and TJ/H2b Analytical Services, efforts were focused on a single model of circuit breaker. Initially, a thorough assessment of interrupter parts was conducted to identify the types and nature of the materials that might be produced in the oil from normal wear and those that might be produced from possible failure modes. This was done using chemical, electrical and optical methods that have been described previously [3, 4]. As a part of the initial study, oil samples were taken from this family of circuit breakers and evaluated using a wide range of tests. Among these tests were particle profile assessment (PPA), dissolved

gas analysis (DGA), moisture content, acidity, power factor and dielectric breakdown voltage.

Using the results of laboratory test data and field evaluations of the condition of these breakers, an algorithm was developed to generate a condition code, diagnostic comments and recommendations. The algorithm uses as inputs dissolved gas data, particle profile data and fluid quality data. The condition codes are integer values ranging from one to four. By convention, increasing numbers reflect poorer condition. The reliability of the algorithm was then determined by increasing the application of BOA to transmission breakers throughout the PG&E system. Units that generated a condition code of four were subjected to an internal inspection. In addition, a number of units that generated a lower condition code were inspected to confirm the validity of the indicated code. Ultimately the study was extended to include distribution class breakers as well..

The result was the development of an effective non-intrusive means to analyze the condition of in-service circuit breakers. After nearly two years of use, over 3000 tanks have been evaluated.

Based on the early success of the BOA program, a similar project was undertaken for LTCs. Initially, LTC components and fluids were scrutinized following the same forensic approach. Using the same test protocols, an algorithm was developed that considers LTC characteristics in addition to the test results. Test results from approximately 500 units were used to develop the algorithm. TASA diagnostics including condition codes, comments and recommendations are generated using the same conventions as for BOA.

Following the development of the BOA and TASA programs the most recent efforts have been focused on the development and implementation of a condition-based maintenance program for transformers. Once again a forensic approach to understanding components and processes has been fundamental to the development of test protocols and the diagnostic algorithm. TCA diagnostics also include condition codes and comments for maintenance prioritization and planning.

Basis of the Methods

Dissolved Gas Analysis

Dissolved gas analysis has been applied successfully for many years to oil-filled power equipment, such as transformers, where current switching is not involved. It has also been applied to load tapchangers with varying degrees of success. A fundamental issue derives from the fact that OCBs and LTCs generate fault gases in normal operation. Developed from the transformer experience, the conventional approach has been to determine what constitutes an elevated gas level and to assign flagpoints. We

have found several difficulties with this approach and have sought alternative ways of assessing deviations from normal behavior. Recognizing that certain gases are characteristic of particular modes of abnormal energy dissipation and that certain gases may be produced in normal operation, characteristic sets of ratios have been developed that we call Hanson's ratios. These ratios are applied to devices that produce gases in normal operation (e.g. OCBs and LTCs) as well as to those that do not.

Particle Profile Assessment

Particle profiling provides important information about the deterioration of materials that result in particle production. Particle profiling can provide information about most components in contact with the oil. This includes information about in-service processes such as fluid degradation, component deterioration, mechanical wear and rust formation. Particle profiling can also provide information about contamination produced during manufacturing and maintenance activities as well as contamination introduced from environmental exposure.

Fluid Quality Assessment

Insulating liquids are generally chosen on the basis of their favorable dielectric characteristics and their chemical stability. These fluids are typically, but not necessarily, mineral-oil based. Silicone fluids, synthetic hydrocarbon fluids, ester-based fluids and also vegetable-based oils are finding limited use in electrical equipment.

For diagnostic purposes, contaminants and degradation products of the insulating materials (fluids and solids) are analyzed. Most commonly, the contaminants and degradation products that are soluble in the oil are analyzed. The presence of these components provides information as to the processes that led to their introduction or caused their formation. For example, one process that is unavoidable is oxidation. Though a generally slow process, its rate is greatly dependent on the temperature and availability of oxygen.

The diagnostic algorithms for each type of equipment are based on the integrated relationships between each of these data, including Hanson's ratios, and the development of these relationships through time.

Application of the Methods

Each of these methods, Breaker Oil Analysis (BOA™), Tapchanger Activity Signature Analysis (TASA™), and Transformer Condition Assessment (TCA™) is applied as a part of a condition-based maintenance program. The application of each method is based on equipment criticality, equipment utilization and equipment event parameters that are intended to insure optimal maintenance planning and scheduling [5].

Case Histories

Oil filled Circuit Breakers

Case 1-Table 1

Lockeford Substation - A Distribution Class Breaker

Dissolved Gas Analysis (ppm)

Hydrogen	2251
Methane	2159
Ethane	887
Ethylene	6055
Acetylene	18490
Carbon Monoxide	1951
Carbon Dioxide	4758
Nitrogen	77485
Oxygen	1939

Particle Profile (counts/100 ml)

Particles 5 to 15 um	1380250
Particles 15 to 25 um	974690
Particles 25 to 50 um	43710
Particles 50 to 100 um	250
Particles 100 um plus	30

Oil Quality

Moisture	111ppm
Dielectric Breakdown Voltage	23kV

The breaker oil analysis indicated a Condition 4. Based on the BOA tank assessment, the breaker was scheduled for open tank inspection.

The inspection revealed:

- Interrupter assemblies that were generally found to be loose.
- Excessive thermal wear in the baffles and arcing nozzles with baffle and nozzle parts wear estimated to be greater than 76% (Figures 1 and 2).
- Moving contact arcing tip erosion estimated to be greater than 76% (Figure 3).

- Signs of excessive heating on the stationary contacts with contact wear estimated to be greater than 50% (Figure 4).

All of the contacts and interrupters were replaced. Since the condition of the oil was poor, it was replaced after the overhaul.

Figure 1

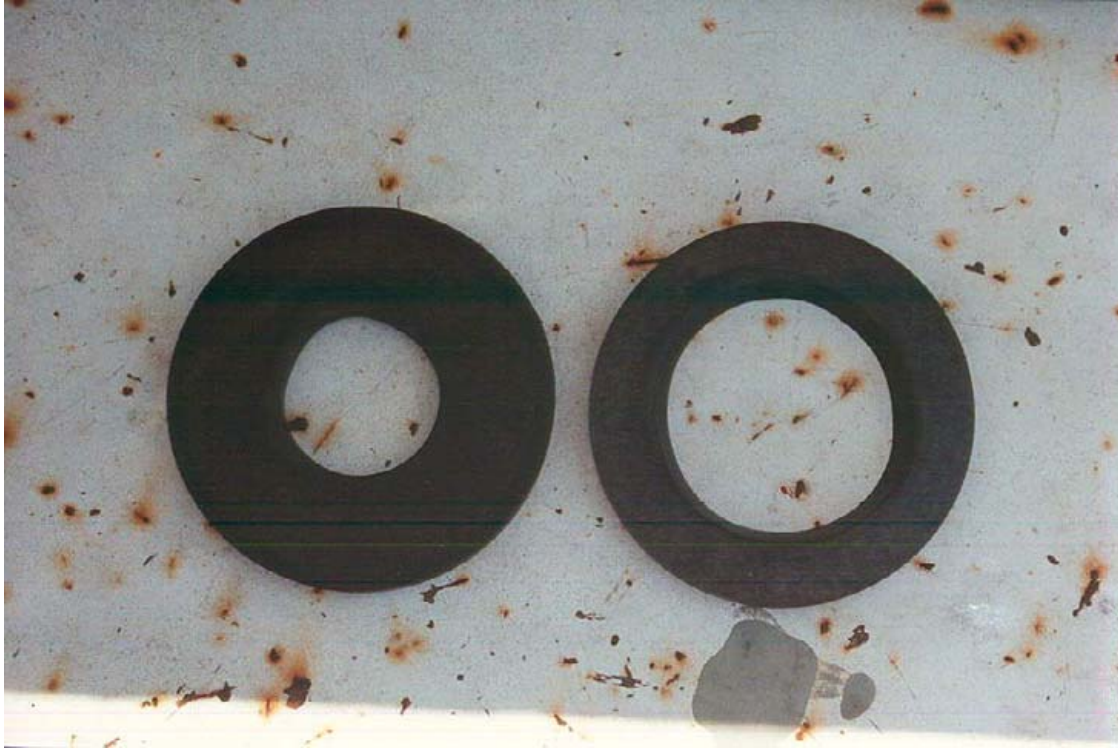


Figure 2

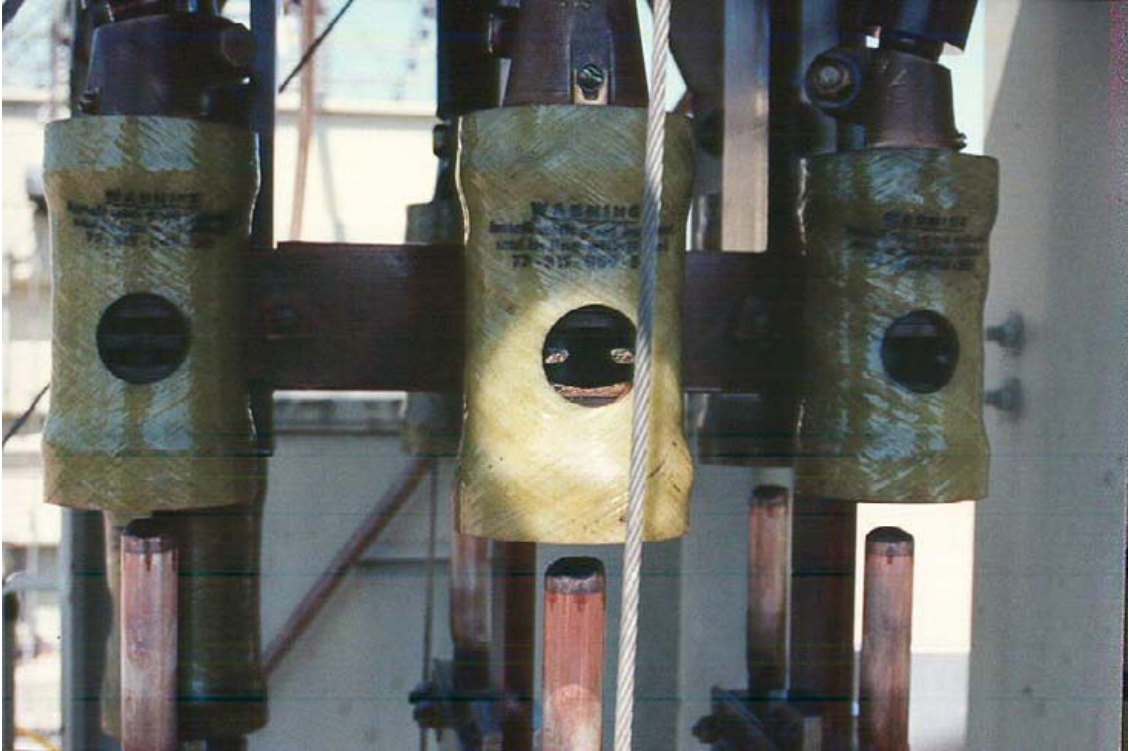
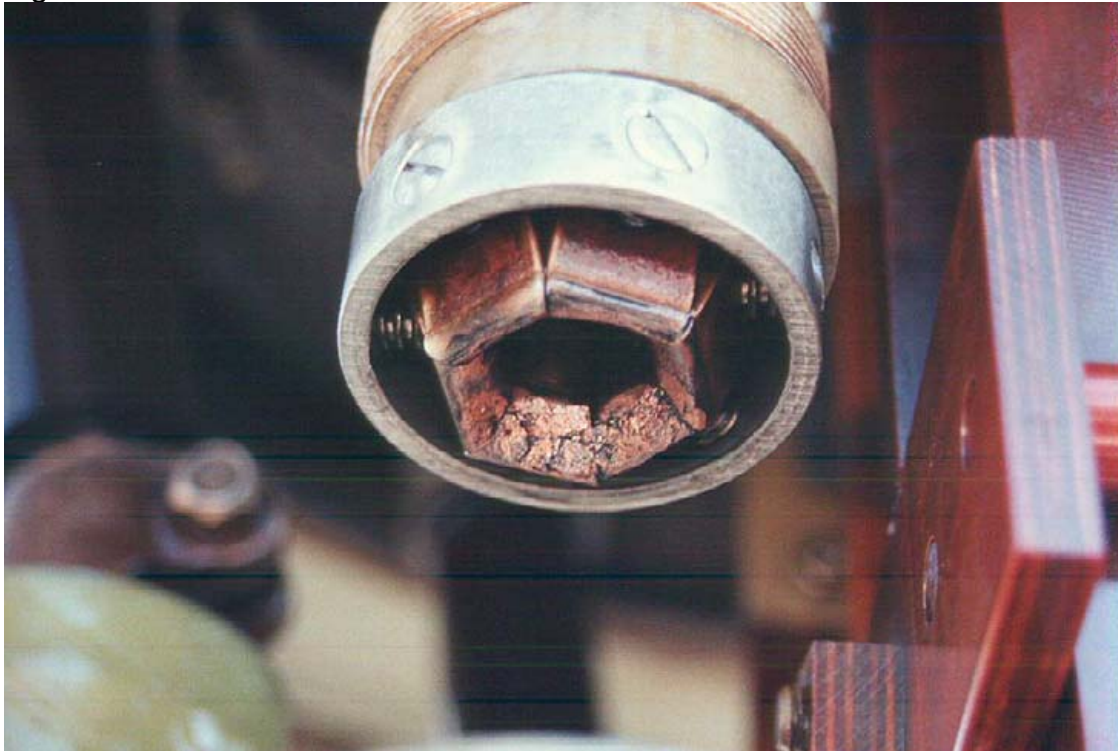


Figure 3



Figure 4



Case II-Table 2
Tudor Substation - A Distribution Class Breaker

Dissolved Gas Analysis (ppm)	A Phase	B Phase	C Phase
Hydrogen	10	6	18
Methane	3	5	3
Ethane	0	0	0
Ethylene	0	0	0
Acetylene	0	0	0
Carbon Monoxide	162	148	176
Carbon Dioxide	1869	1260	1149
Nitrogen	55783	62516	51566
Oxygen	11239	10504	7205
Particle Profile (counts/100ml)			
Particles 5 to 15 um	1215510	1539110	1505570
Particles 15 to 25 um	833330	555910	425580
Particles 25 to 50 um	103560	69860	26480
Particles 50 to 100 um	1420	2570	520
Particles 100 um plus	10	90	20

Oil Quality

Moisture	59ppm	47ppm	36ppm
Dielectric Breakdown Voltage	23kV	22kV	25kV

The breaker oil analysis indicated a Condition 4 for each phase. Based on these BOA tank assessments, all three tanks were scheduled for open tank inspection.

The inspection revealed:

- Loose connections in all three phases.
- All six of the arcing contacts were pitted and burned, showing about 65% erosion.
- Rotor bearing wear estimated to be 90% in the A and C phase tanks.
- Lithard breaking away from all six bushings showing approximately 90% deterioration.

Load Tapchangers

Unlike the situation with oil-filled circuit breakers, an earlier and more extensive fluid testing program had been in place for LTCs. This afforded the opportunity to use existing test and inspection data to evaluate the Tapchanger Activity Signature Analysis assessments prior to implementing them. Cases III through VI in Table III demonstrate the success of this evaluation.

Cases III to VI-Table 3

Dissolved Gas Analysis (ppm)	Case III ¹	Case IV ²	Case V ³	Case VI ⁴
LTC/Regulator	MLT32	UZD	Reg	UTT B
Hydrogen	69	1317	591	859
Methane	450	608	6088	843
Ethane	137	841	2626	414
Ethylene	329	2278	11433	3574
Acetylene	41	8739	193	5155
Carbon Monoxide	164	312	294	180
Carbon Dioxide	837	4576	934	3454
Nitrogen	56737	61144	62286	63962
Oxygen	25812	6863	26671	7415

1. The tapchanger activity signature analysis indicated a Condition 4 heating problem for the unit in Case III. Earlier 'gas-level' based diagnostics indicated a Condition 3. The findings of an infrared scan forced the unit out of service and the B phase reversing switch was found to be badly coked.

2. TASA indicated a Condition 4 with excessive arcing for the unit in Case IV. An arcing contact was found to have been burnt off when this unit was inspected.
3. TASA indicated a Condition 4 with heating and partial discharge for the unit in Case V. The inspection revealed heavy coking on the reversing switch contacts. In addition, the main stationary and moving contacts were found to be heavily worn.
4. TASA indicated a Condition 4 with heating for the unit in Case VI. Inspection of this unit had revealed that the moveable contacts had started to coke.

Cases VII to VIII-Table 4

Dissolved Gas Analysis (ppm)	Case VII	Case VIII
	East St TLH20	East ST2 TLH20
Hydrogen	82	1199
Methane	56	10252
Ethane	48	6075
Ethylene	148	36375
Acetylene	2	908
Carbon Monoxide	494	252
Carbon Dioxide	4257	1710
Nitrogen	76117	68244
Oxygen	16790	15114

Early in the development of the TASA diagnostic protocol, an LTC in our system failed catastrophically, destroying the transformer as well. Application of TASA to a sister unit using earlier test data (Table IV, Case VII) gave a Condition 4 indicating heating. Another sample was taken (Table IV, Case VIII). This time TASA gave a Condition 4 and indicated a critical level of heating. Inspection revealed severely coked reversing switch contacts on two phases (Figure 5).

Figure 5



Transformers

Transformer Condition Assessment is currently at the stage of confirming findings with evaluations and predictions. One unit currently being studied is shown in Table5.

CASE VIII-Table 5

Dissolved Gas Analysis (ppm)	1	2	3	4
Hydrogen	38	65	223	265
Methane	341	453	893	1124
Ethane	150	193	340	430
Ethylene	651	792	1610	2034
Acetylene	0	0	0	0
Carbon Monoxide	41	59	53	88
Carbon Dioxide	1471	1642	2586	3245

Table 5 cont.

Particle Profile (counts/100ml)	
Particles 5 to 15 um	56010

Particles 15 to 25 um	5485
Particles 25 to 50 um	2065
Particles 50 to 100 um	195
Particles 100 um plus	5

Oil Quality

Moisture	17ppm
Interfacial Tension	34ppm
Acid	0.005
Dielectric Breakdown Voltage	23kV
PF @ 25	0.027
Oxidation Inhibitor	0.038

The Transformer Condition Assessment indicates coking or charring possibly occurring at the no load tapchanger.

Conclusion

It is important to recognize that use of these programs:

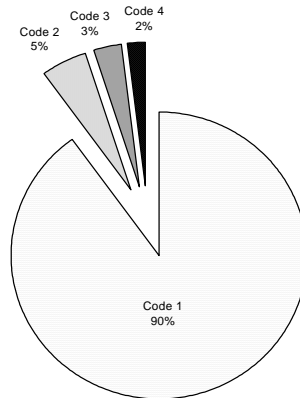
- Permits maintenance personnel to correlate the oil test results to the serviceability of the equipment.
- Allows the identification of operational faults and improper operation of the equipment.
- Incorporates guidance for when maintenance is to be performed as components near the end of their useful life or when abnormal conditions threaten the life or safe operation of the equipment.
- Allows for the scheduling of maintenance using prioritization based on condition codes.
- Avoids unnecessary maintenance.
- Alerts maintenance personnel to potential dangers in handling or processing the oil.

Application of our diagnostic program allows maintenance personnel to depart from traditional time-based maintenance practices by diagnosing the condition of in-service units to determine when equipment maintenance becomes necessary. This approach provides significant cost savings.

Projections for maintenance costs based on current operating experience and the diagnostic evaluations from an equipment survey indicate that these maintenance costs may be reduced by as much as eighty-four percent (84%) compared to past practices. The variation in savings is dependent on the interval of the maintenance period and the

percentage of units that have condition codes that are deemed to require attention in a given year. Figures 5 and 6 illustrate the development of these projections.

Figure 6
Distribution of Equipment by Condition Code



Initially, all units to be included in the maintenance cost assessment were tested and categorized by condition code. The results produce a distribution similar to the one shown in Figure 5. As a rough estimate, assume that all units with Condition Code of 4 will require maintenance in the current year and that all other units will not. For most utilities, this number will be smaller than the number scheduled for maintenance on a time-interval basis. With the completion of the second testing cycle, improved estimates for the number of units requiring maintenance in any given year can be made. Successive testing cycles will provide additional data to continually refine the estimate.

Comparison of the number of units that would be maintained by each approach or the percentages of units that would be maintained by each approach provides an estimate of the savings. A better estimate is obtained by comparing the actual costs for the condition-based maintenance to the historical costs for the time-based maintenance.

Figure 7

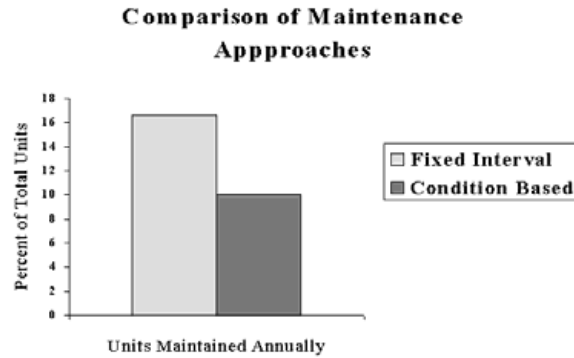


Figure 6 is an example that compares a six-year fixed-interval maintenance program to a condition-based program that results in an average maintenance interval of ten years. Using the condition-based approach, if 10% of all units would be maintained annually compared to 17% of all units that would be maintained on a six-year fixed cycle, the annual average condition-based maintenance would be sixty percent of the maintenance performed using the fixed interval approach. This would result in a maintenance reduction of forty percent!

Table II indicates the savings that would result for various combinations of fixed-interval maintenance periods with the percentage of units requiring attention based on condition codes.

Table 6
Percent Savings in Maintenance

		Fixed-Year Maintenance Interval (Years)				
		4	5	6	7	8
% of Units	4 %	84	80	76	72	68
Requiring	6 %	76	70	64	58	52
Maintenance	8 %	68	60	52	44	36
Based on	10 %	60	50	40	30	20
Condition Code	12 %	52	40	28	16	4

The savings indicated in Table 6 are impressive especially considering that equipment reliability is not compromised.

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