# Transformer Life Extension: Use of Paper Degradation Products for Diagnostics and Condition Assessment

*Phase 1—Interpretation Guide for Furanic Compounds in Oil*

**1015937**

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Technical Update, December 2008

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This document was prepared by

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The document describes research sponsored by the Electric Power Research Institute (EPRI) and British Columbia Transmission Corporation (BCTC).

The publication is a corporate document that should be cited in the literature in the following manner:

*Transformer Life Extension: Use of Paper Degradation Products for Diagnostics and Condition Assessment, Phase 1—Interpretation Guide for Furanic Compounds in Oil.* EPRI, Palo Alto, CA and BCTC, Vancouver, BC: 2008. 1015937.

# PRODUCT DESCRIPTION

In this work, data were gathered from previous research at Powertech Labs, literature publications, and from BC Hydro and British Columbia Transmission Corporation (BCTC) databases. These data were used to establish correlations of furanic compounds in oil with the degree of polymerization values ($DP_v$) of insulating paper to estimate the end of life and improve transformer diagnostics.

## Results and Findings

The literature review indicated that up to now most of the equations relating $DP_v$ of paper with 2-furaldehyde (2-FAL) concentrations in oil are for transformers with regular kraft insulating paper. Because most of the transformers in North America use thermally upgraded paper in their windings, more intensive research relating $DP_v$ of mixed paper systems to the level of furanic compounds is needed. Moreover, data on in-service transformers were used to derive correlations of $DP_v$ of paper with 2-FAL concentrations in oil. It is recommended that separate correlations be used in interpreting furan results from transformers with thermally upgraded paper and for transformers with kraft paper. Finally, a percentile approach was also examined, this approach took into account similar transformers, and the distribution of 2-FAL was plotted against the number of units. Using these data, an algorithm was also developed to help maintenance personnel interpret the results of 2-FAL obtained from laboratories.

## Challenges and Objectives

Currently, 2-FAL is widely used as a marker compound that is specific to the degradation of transformer paper. However, there is evidence to suggest that this compound is not the best-suited marker for thermally upgraded paper used in the windings of 65°C rise transformers, as is commonly found in North America. There is a need for the identification of marker compounds better suited for mixed paper systems. Off-line analysis for the presence of these compounds in oil is now used as a transformer diagnostic indicator on a regular basis. This approach, although convenient and widely used, presents a significant drawback in terms of its accuracy and reliability. The results between long sampling intervals may be misleading because some of the furanic compounds degrade with time and temperature. Only on-line transformer monitoring can identify both temperature and chemical indicators characteristic of paper degradation and specific faults. This “thermo-chemical” model is needed to allow us to obtain a continuous picture of the insulation status and evaluate the conditions of operational transformers in real time. Although considerable progress has been made, in order to achieve the above goals, many issues still remain unresolved. The complex nature of transformers coupled with a multitude of stress factors and transient operating parameters makes the correlation between fault products, diagnosis, and loss of life estimation extremely difficult. To improve our understanding of transformer diagnostics and condition assessment, the Electric Power Research Institute (EPRI) has undertaken a research program to address the following issues:

- Lack of a guide or interpretation algorithms that more accurately relates furanic compounds in oil to the $DP_v$ of the paper and the remaining life of transformers containing kraft or thermally upgraded paper.
- Identification of marker compounds better suited for the determination of the condition and the $DP_v$ of thermally upgraded and mixed paper systems

- Development of sensors or detection systems of key marker compounds suitable for on-line monitoring

## Applications, Value, and Use

The life expectancy of a transformer is determined by the condition of the paper insulation. The concentration of furanic compounds in the dielectric fluid of a transformer has been found to be a good indicator of the condition of the paper and other cellulosic materials. However, because furanic compounds are an indirect measurement of the condition of the paper and influenced by many factors, care should be taken when interpreting the results. This work aimed to assist and guide maintenance personnel with the interpretation of the results of furanic compounds.

## EPRI Perspective

Detailed knowledge of the type of paper decomposition products, their amounts, and their rate of formation is essential for transformer diagnostics and condition assessment. The potential benefits to the utility industry are enormous and include the following:

- Early detection of transformer insulation hot spots that could lead to unscheduled outages or catastrophic failure.
- Allowance for condition-based maintenance of transformers, which could result in reduced maintenance or avoid damage because of insufficient maintenance.
- Extension of transformer service life by preventing unsafe overload conditions.
- Optimized performance as a result of safely operating transformers in excess of the nameplate capacity.
- More accurate thermal models to provide overload management capability during emergency situations or to meet short-term demand needs.
- Potential for dynamic loading.
- Estimation of loss of life and remaining life of transformers.
- Reduced need for the capital investment in new transformer units.

## Approach

This report addresses only Phase 1 of a multiphase project. It is based on previous work, experience, and knowledge of Powertech Labs Inc. in the area of paper degradation and degradation products. Task 1 consisted of examining results from previous work and performing a literature search on technical papers relating the use of furan compounds as an indicator of transformer end of life. Task 2 involved performing a statistical analysis and establishing trends of furans with type of paper and other operational parameters and their relating actual $DP_v$ results from paper to the furans in oil. With the furan results adjusted for specific transformer designs, an algorithm was developed to determine the action to be taken for specific circumstances.


## Keywords

Furanic compounds
Degree of polymerization
Thermally upgraded cellulose paper
End-of life of transformers
Power transformer diagnosis

# ACKNOWLEDGMENTS

EPRI would like to thank Jim Gurney and Mike Lau of BCTC and David Olan of BC Hydro for providing valuable advice.

# CONTENTS

# 1
# INTRODUCTION AND BACKGROUND

## Introduction

In-service transformers are subjected to a combination of electrical, thermal, mechanical, and environmental stresses. When these transformers exceed their design limits, faults may develop in the form of partial discharge, arcing, or hot spots—resulting in the formation of fault products. Fault progression will inevitably lead to failure if the dielectric integrity is compromised. The type, magnitude, and temperature of faults dictate the type, quantity, and rate of formation of fault products. Detailed knowledge of product type, amount, and rate of formation is essential for condition assessment and equipment diagnosis. Of particular concern is the development of a hot spot in the paper insulation that results from overload or localized heating, as this will ultimately determine the life of the transformer. This is because the oil can be reconditioned by conventional treatment or simply replaced, but the paper degrades through an irreversible process of depolymerization.

A high-voltage transformer is expected to operate reliably for up to 40 years; however, the fundamental life-limiting factor is related to the degradation of paper insulation of the windings. Thus, it is generally accepted that the technical end of life of a power transformer is determined by the condition of the insulating paper, although other factors may cause premature failure. The beginning of decrease in reliability is generally associated with a variety of causes, many of which are design specific. Insulating paper consists of approximately 90% cellulose, 6–7% hemi-cellulose, and 3–4% lignin. In-service paper deteriorates primarily by cleavage of the large cellulose chains because of temperature, reaction with water, oxygen, or any combination of these. The paper can eventually become discolored, brittle, and fragile, at which point its physical and chemical properties are degraded to such an extent that it puts the electrical integrity of the equipment at risk. Therefore, it is important to find reliable and sensitive methods to monitor the condition of the paper for incipient faults and risk of failure in order to estimate its remaining life. Historically, changes in the degree of polymerization ($DP_v$) of the paper have been used to estimate its condition from its new state down to extreme degrees of deterioration and estimate expected lifetimes. However, the $DP_v$ method is intrusive, as it requires sampling the paper from a transformer and is therefore not appropriate for continuous monitoring.

The transformer insulation system consists of cellulose products (mostly paper) and a dielectric fluid (typically mineral oil). When a hot spot develops in the transformer windings, the increase in temperature causes the oil/paper insulation system to degrade and produce a variety of new compounds, including fault gases ($H_2$, $CH_4$, $C_2H_2$, $C_2H_4$, $C_2H_6$, CO, and $CO_2$), moisture, volatile organic compounds (VOCs), and non-volatile organic compounds (NVOCs). Compounds that originate exclusively from cellulose decomposition have been identified and include 2-furaldehyde (2-FAL) and furyl alcohol (2-FUROL) as the main products along with several other oil-soluble furanic and non-furanic compounds at lower concentrations in addition to CO, $CO_2$, and moisture. Of these, 2-FAL has been related to the $DP_v$ of the paper and used as the leading indicator of the remaining life of transformers.

Paper degradation is primarily related to temperature but is accelerated by moisture, oxygen, acids, and other contaminants. The type and level of these compounds is also strongly dependent on the type of paper (kraft or thermally upgraded). Detailed knowledge of the type of paper decomposition products, their amounts, and their rate of formation is essential for transformer diagnostics and condition assessment. The potential benefits to the utility industry include the following:

- Early detection of transformer insulation hot spots that would otherwise lead to unscheduled outages or catastrophic failure.
- Allowance for condition-based maintenance of transformers instead of time-based service intervals. This will result in reduced maintenance in most cases and avoid damage because of insufficient maintenance in others.
- Extension of transformer service life by preventing unsafe overload conditions.
- Optimized performance as a result of safely operating transformers in excess of the nameplate capacity.
- More accurate thermal models to provide overload management capability during emergency situations or to meet short-term demand needs.
- Potential for dynamic loading.
- Estimation of loss of life and remaining life of the transformer.
- Reduced need for the capital investment in new transformer units.

Although considerable progress has been made, in order to achieve the above goals, many issues still remain unresolved. The complex nature of transformers coupled with a multitude of stress factors and transient operating parameters makes the correlation between fault products, diagnosis, and loss of life estimation extremely difficult. To better appreciate the magnitude of this task, it is helpful to understand how a fault develops and progresses.

## Anatomy of Solid Insulation Fault

When a hot spot starts to develop in the paper insulation, the localized rise in temperature causes the production of a variety of fault compounds as discussed previously, most of which have been determined and reported previously. For a slowly developing hot spot, the fault compounds will dissolve in the oil. The ability of the oil to hold these products in solution depends on their **solubility**. Thermal and forced circulation of the oil will carry the dissolved fault products around the transformer, where they will be **diluted** by the bulk oil and come into contact with cooler paper insulation. A portion of the more polar fault compounds will be reabsorbed by the paper. Fault gases and volatile compounds will be gradually lost because of gasket leaks and **exchange** through the conservator or headspace. Over time, the less chemically stable fault compounds will decrease because of thermal breakdown or chemical reactions with moisture, oxygen, or other contaminants. Organic compounds that are not readily oxidized and have a low vapor pressure will stay in the transformer, within the oil/paper insulation. If the hot spot condition stabilizes, a dynamic equilibrium between generation and loss of fault products may be reached.

However, if the fault progresses, the rate of production of fault products increases to a maximum and then declines as the amount of paper available is consumed. The concentration of these products in oil will also increase to a maximum, stabilize, and then slowly decrease as they leak out or decompose. At this point, the paper will rapidly degrade until it cracks or falls apart, and a catastrophic failure of the unit can occur. As the load and temperature fluctuate, the fault compounds will **migrate** between papers and oil as dictated by their **partition coefficient**. Dynamic partition between the paper and the oil will continue on a daily basis following the load cycles of the transformer. In a typical operational transformer, these products are in a dynamic state between the oil, paper, and gas phases. Their concentrations at any given time are a function of their solubility properties, partition coefficients, chemical stability, and losses to the surrounding areas—all of which are affected by temperature and daily load variations.

It is apparent from the above discussion that in-service transformers are not in equilibrium but rather in a **dynamic state** affected by its operational parameters. Unfortunately, most of these parameters are not known, making conclusions based on an oil sample at a given time ambiguous and inaccurate or worse, erroneous or misleading. For example, although moisture and oxygen accelerate the paper aging process, using their concentration in the bulk of the oil to calculate the acceleration factor can be misleading. This is because the moisture level in the paper at the hot spot is likely much lower as the higher temperature of the conductor drives it out. Similarly, the oxygen level at the hot spot is likely lower as it will have been partially depleted in the surrounding areas.

## Background

Considerable work has already been done by Powertech Labs and worldwide in the area of paper aging and its relation to transformer diagnostics and condition assessment. Most of the research has focused on the use of furanic compounds, specifically 2-FAL. However, in interpreting the furan test results, caution is warranted. In previous studies, it was shown that furan level in European transformers is higher than in those in North America [1]. Others have also made this observation [2]. This may be due to the predominant use of thermally upgraded paper (TUP) in North American transformers as opposed to mostly non-upgraded regular kraft paper in European units. Paper is thermally upgraded by being impregnated with additives, the most common being dicyandiamide (DICY), which helps to slow thermal degradation and make it more stable under higher temperatures. Therefore, the type of insulating paper (kraft or thermally upgraded paper) influences the type and amounts of products formed because of degradation.

To aid in furan interpretation, some researchers have developed equations to relate the furan concentration in oil with the $DP_v$ of the paper [3, 4]. These equations can be used to predict the $DP_v$ from the furan results. However, caution must be used as these equations generally calculate the average DP for the entire insulation system and not the paper at the hot spot. In addition, most of the equations were derived from controlled laboratory experiments using regular kraft paper and/or from transformers using non-upgraded paper. They may not be applicable to furan results from transformers with upgraded paper or mixed paper systems, such as many of those in North America. In fact, recent studies suggest that 2-FAL may not be the best indicator of degradation or of the $DP_v$ of thermally upgraded paper insulation.

In previous work, we have detected many compounds that originated specifically from thermally upgraded paper. Our results indicated the formation of several compounds that may be more amenable to on-line monitoring. However, there is a need to fully identify and characterize which products are better suited as diagnostic indicators for monitoring the degradation of mixed (kraft and thermally upgraded) paper systems. Such knowledge is necessary for more accurate estimation of the condition of the paper and detection of potential hot spots in mixed insulating paper transformers.

Most of the research to date has been done at the bench-scale level under controlled conditions. Although this approach is adequate for determining fundamental parameters, it lacks the sophistication of simulating actual operating conditions. What is needed is a model based on actual transformers, which relates furans to the $DP_v$ of thermally upgraded paper and mixed paper systems.

# 2
# SCOPE AND OBJECTIVES

## Scope

Although considerable progress has been made, in order to achieve the desired goals, many issues still remain unresolved:

- Lack of a guide or interpretation algorithm that more accurately relates furanic compounds in oil to the $DP_v$ of the paper and the remaining life of both 55°C (kraft paper) and 65°C (thermally upgraded paper) rise transformers
- Identification of marker compounds better suited for the determination of the condition and the $DP_v$ of thermally upgraded and mixed paper systems
- Lack of sensors or detection systems of key marker compounds suitable for on-line monitoring

Off-line analysis for the presence of these compounds in oil is now used as a transformer diagnostic indicator on a regular basis. This approach, although convenient and widely used, presents a significant drawback in terms of its accuracy and reliability. This is because the location and time of sampling have a large influence on the furanic results. An active fault between sampling intervals may be missed—worse, it may progress to failure before the next scheduled sample. The results between long sampling intervals may be misleading as some of the furanic compounds degrade with time and temperature. Only on-line transformer monitoring can identify both temperature and chemical indicators characteristics of paper degradation and specific faults. This “thermo-chemical” model will allow us to obtain a continuous picture of the insulation status and evaluate the conditions of operational transformers in real time.

The project work will be carried out in phases as described below; however, this report will cover only Phase 1. Work in other phases will be reported in a future update.

### *Phase 1: Interpretation Guide for Furanic Compounds in Oil*

Although furan-in-oil testing is an accurate and well-established procedure, the results require expert interpretation. The data must be reviewed in the context of sampling conditions (oil temperature), insulation structure, unit operating history (oil processing), and other test results (such as on dissolved gases and moisture). Unfortunately, there are no guidelines or algorithms available to establish the correlation of furanic compounds to $DP_v$. Work in this phase is aimed at developing an algorithm for transformer maintenance engineers to use as a guide.

### *Phase 2: Identification of Marker Compounds*

This will include the identification of marker compounds that are better suited as indicators for monitoring a mixed paper system (kraft and thermally upgraded paper) degradation.

### *Phase 3: Development of On-Line Monitoring*

This includes the development of on-line monitoring of marker compounds from paper degradation. Currently, there are no commercially available monitoring systems suitable for on-line detection of transformer paper degradation products. A considerable amount of research has been carried out by Powertech Labs Inc., which included several patents related to this field of work. This proposed research will exploit and build on this knowledge.

### *Phase 4: Field Trials of On-Line Monitoring*

This phase depends on the results obtained from Phases 2 and 3. After all of the above tasks have been successfully completed, a prototype-monitoring unit will be built to monitor the target product. The unit will be evaluated in the laboratory for performance and then installed in the field on an in-service transformer.

## Objectives

The main objective of Phase 1 of this project is to develop an interpretation guide for furanic compounds in oil. This will involve making use of existing data to gain a comprehensive understanding of the key factors affecting the use of furanic compounds as an accurate indicator of transformer end of life and to make recommendations on how to improve transformer end-of-life predictions. This will be carried out by:

- Building on the most up-to-date information on furanic compounds as indicators of the end of life of a transformer. It will involve reviewing previous research done by Powertech and performing a literature search on technical papers.
- Performing statistical analysis of BCTC's, BC Hydro's, and other databases and establish trends of furans with different factors.
- Developing an algorithm while taking into account all relevant parameters and results and using them to calculate the $DP_v$ of paper, the remaining life of a transformer, and any action to be taken.

# 3
# CURRENT KNOWLEDGE

A literature review was conducted based on search criteria using the following key words and phrases:

- Furanic compounds and degree of polymerization
- Thermally upgraded cellulose paper
- Furfural concentration and transformers
- End of life of transformers
- Power transformer diagnosis
- Degree of polymerization
- Insulating papers
- 2-furfuraldehyde

The search focused on the period of 1991–2008, with links to the 1980s. The earlier period was addressed in the case of research done on kraft paper in European transformers and their correlation to the end of life of a transformer. A few recent papers have focused on the correlation of the end of life of a transformer with TUP, which is mainly used in North American transformers.

Previous furan studies have focused either on details of the analytical technique or experiments with laboratory analogs of transformers. A typical study in the laboratory involves heating of paper and oil in a container with perhaps some copper and steel present to make the system more similar to a transformer. Such studies are excellent for the testing of materials but not very similar to real transformers for several reasons. First, transformers are dynamic systems with constantly fluctuating electrical loads and temperatures; as such, they do not have uniform internal temperatures as a test container would have in an oven. Second, transformers in the field are subject to various uses that may affect the oxygen and/or water content of the oil. In practice, it is difficult to maintain the dry and degassed protocols specified in most experiments over the lifetime of a real transformer.

In this section, emphasis was placed on the interpretation of furan results as listed in the literature and included the following:

- Different factors that influence 2-FAL concentration in oil
- The stability of furanic compounds in oil as a function of temperature, moisture, and oxygen
- Equations derived from both experimental and analytical investigations concerning the correlation between furanic compounds, DP, and the end of life of transformers. The accuracy of these equations will also be analyzed.

## Interpretation of Furan Results

When the cellulose polymer chain from paper breaks down, it may liberate a glucose monomer unit. Further decomposition may lead to one of a family of derivatives of 2-FAL. These derivatives, collectively known as *furanic compounds*, are partially soluble in oil [5]. After formed, they will redistribute throughout the solid insulation and the oil phase. Their concentration in oil can be determined through established analytical test methods.

Many trend evaluations and model investigations were performed to identify a correlation between furanic compounds and $DP_v$ values. The results described in the literature are controversial [6, 7, 8]. A trend correlation between furanic concentration and $DP_v$ value exists, but it is not clear whether a common mathematical relationship between $DP_v$ value and furanic compounds in oil may be established for the life assessment of transformers.

As discussed earlier, many factors influence the 2-FAL concentrations in oil and its application both to the condition of paper and to transformer diagnostics, including the following:

- **Hot spot temperature.** Temperature is the main factor that influences the formation of 2-FAL from paper degradation. However, the temperature within a transformer is not uniform and fluctuates because of different loading conditions. In addition, heating resulting from load and cooling by the oil creates complex temperature gradients throughout the insulation system that affect the formation and distribution of furanic compounds.
- **Moisture and oxygen.** Both of these have a large accelerating influence on the production of furanic compounds. In fact, recent investigations [9] indicate that at lower temperatures, the effect of moisture is dominant. Moisture content also influences the distribution of furanic compounds between the paper and the oil [10]. Therefore, while taking a 2-FAL measurement, it is important to measure the moisture content in oil. Oxygen also has an accelerating effect on paper degradation but to a much lesser extent.
- **Paper type.** Thermally upgraded paper produces much lower amount of furanic compounds in comparison to normal kraft paper. The ratio of these products among themselves (patterns) is also different. Thermally upgraded paper produces far more 2-furyl alcohol (2–5 times the amount) than kraft paper.
- **Bulk oil temperature.** The oil temperature will affect the long-term stability of furanic compounds in oil. The actual concentration of 2-FAL in transformer oil is the difference between the rate of formation and the rate of degradation. The bulk oil temperature also determines the partition coefficient of furanic compounds between oil and paper; thus their concentration in oil may vary with temperature at the time of sampling.
- **Transformer design.** The design of the transformer (ratio of paper to oil) and cooling conditions are also very important. The ratio of paper to oil in a shell-type transformer can be twice that of a typical core-type transformer. The higher amounts of paper will influence the formation of furanic compounds in oil and their distribution in the bulk of the paper.

- **Operating history.** Furanic compounds are distributed between oil and paper; their relative amounts depend on the partition coefficient of a specific compound at a given temperature. Most furanic compounds are polar in nature and thus have a preference for the paper. Oil change or reclamation removes furanic compounds from oil; however, furans absorbed by the paper and the residual oil in the paper will slowly leach out and re-equilibrate with the replacement oil. The amount of leach-back will be determined by the partition coefficients and surrounding temperature. During this leach-back period, the increase of furanic compounds is the sum of paper degradation and re-equilibration.
- **Oil type and condition.** The type of oil used is also very important. Some oil inhibitors have a certain protective influence on the formation of furanic compounds in comparison to non-inhibited oils. Therefore, while measuring the level of furanic compounds, an eye should be kept on the level of the inhibitors in the oil. High levels of oil decomposition products may also accelerate the formation of some furanic compounds while reducing the stability of others.

These factors are discussed in more detail next.

## Effects of Temperature, Water, and Oxygen on Paper Insulation Life

### *Effect of Temperature*

Transformer materials are carefully selected to withstand operating temperatures, and the effect of aging is most pronounced for cellulose-based materials that are in contact with copper windings. While long-term thermal stresses lead to progressive deterioration, significant localized damage may occur near hot spots over short periods of time. Conductor-wrapped paper and some pressboard components next to the core and the coils are made from the highest quality pulp and may be thermally upgraded to withstand temperatures in the 130–140°C range.

A typical transformer thermal profile will have a range of temperature zones. The coolest temperature is at the bottom, and it increases from bottom to top. The combined results of heating from the windings, cooling by the oil, and design inevitably lead to hot spots near the top of the windings. A simplified thermal diagram for evaluation of the hot-spot temperature is shown in Figure 3-1. Temperature differences in different zones can be substantial. For example, the hot spot temperature can be 15°C or more higher than the top oil temperature and the top oil temperature more than 15°C higher than the average bulk oil temperature. A thermal model has been developed and published in IEEE STD C57.91.1995. This model is commonly used to estimate the hot spot and average temperatures of operation transformers from their top oil temperature. For example, in a normal operation, the bulk of the insulation rarely experiences temperatures in excess of 105°C. This corresponds to a 65°C temperature rise over ambient temperature (maximum of 40°C), which is the design rating at full load. The 65°C rise is for the top oil only. Typical maximum and average windings will be approximately 120°C and 105°C, respectively. The average temperature is taken to be approximately 15°C below the average of the winding temperature, or approximately 90°C.

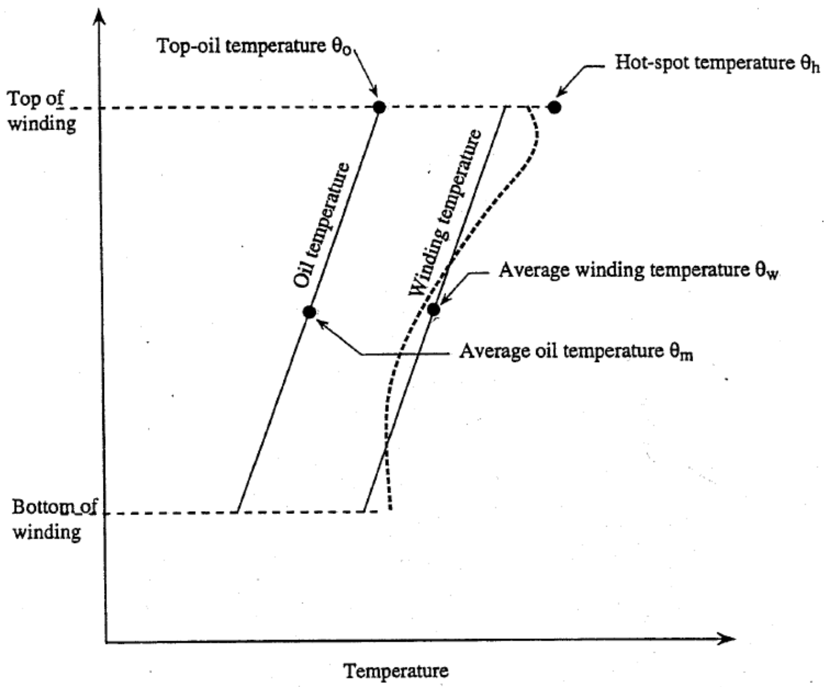


**Figure 3-1**
**Simplified thermal diagram for evaluation of the hot-spot temperature**

The thermal decomposition of paper accelerates rapidly with temperature. Montsinger [11] noted that the rate of deterioration of mechanical properties of paper doubled for each 7°C increase in temperature, so hot spots are particularly prone to early failure and generally viewed as the weakest spot. There is some evidence to show that the decomposition process accelerates more rapidly above 140°C.

There is a consensus that decomposition follows the Arrhenius equation over the temperature range of 130–200°C, as shown in Equation 3-1:

$$K_o = A' \, EXP \, [B / \Theta + 273]$$

**Equation 3-1**
**Arrhenius equation**

Where:

$A'$ and B are empirical constants

$\Theta$ is the temperature in °C

Based on the above equation, the relationship was further refined and used for transformer life definition as shown in Equation 3-2. This equation expresses the dependence of the aging rate on the temperature alone.

$$\text{Per unit life} = A\ \text{EXP}^{[B/\Theta_H + 273]}$$

**Equation 3-2**
**Dependence of aging rate on temperature**

Where:

A is a modified per unit constant, derived from the selection of 110°C as the temperature established for "one per unit life"

B is the same aging rate slope as in Equation 3-1

Based on the above equation, IEEE STD C57.91.1995 has determined that for a winding hot spot temperature of 110°C, a normal life of 180,000 hours is a reasonable expectation for both distribution and power transformers. This corresponds to 20 years for a well-dried and oxygen-free insulation. Unfortunately, the effects of different levels of moisture and oxygen are not included in the calculations. When an absolute value is placed on the time required to reach a selected end point, the effect of all of the significant variables—that is, heat, water, and oxygen—must be considered.

### *Effect of Oxygen*

According to Fabre and Pichon [12], oxygen increases the rate of degradation of paper containing 0.3 to 5% moisture in oil by a factor of 2.5. The effects on predicted insulation life are shown in Table 3-1. In a model transformer experiment [13], it was found that the oxygen level in the oil increased initially as the paper out-gassed but fell slowly as it was consumed by the reaction with paper and oil. If the dissolved oxygen level is maintained below 2000 ppm, the rate of oxidation of the oil is reduced substantially. Maintaining the level below 2000 ppm can further reduce the acceleration because of the oxygen to a sixteenth of that at saturation (30,000 ppm). The detrimental effects of oxygen on the paper are to some degree ameliorated by the presence of copper, which promotes the oxidation of oil.

**Table 3-1**
**Effect of moisture and oxygen on lifetime predictions (years) from Fabre and Pichon [12]**

| Condition of Aging | Temperature (°C) | | | |
|---|---|---|---|---|
| | 80 | 90 | 100 | 110 |
| Paper under vacuum and containing 0.5% water | 1200 | 350 | 95 | 26 |
| A free-breathing transformer maintained in contact with perfectly dry air | 480 | 140 | 67 | — |
| A free-breathing transformer with 50 ppm water in the oil | 67 | 30 | 15 | — |

### *Effects of Water*

Early studies [12] indicated that the rate of degradation of paper increased in direct proportion to the water content and predicted insulation life estimated in Table 3-1. However, more detailed studies later concluded that, during the later stages of degradation, the logarithm of the rate is proportional to the moisture level.

Because water is also a product of degradation, the moisture level in paper increases with aging [14, 15, 16] at a rate of a 0.5% increase for each time the $DP_v$ of the cellulose is halved by degradation [17]. This results in a decrease in electrical strength:

$$\text{Water concentration} = 0.5 \text{ Log } [DP_0/DP_t]/\text{Log } 2$$

Calculations of the amount of water generated by the degradation of paper indicate an approximate rate of 25 ng/g of paper per hour. In thick layers of paper, diffusion to the surface will inhibit the release of this moisture, and enhanced degradation rate can occur. In practice, moisture levels in paper insulation have been observed to increase from <0.5 to 4%, and in extreme cases, 4–8% over their lifetime. Because the rate of degradation at 4% moisture in the paper is 20 times greater than at 0.5%, at normal service temperatures, moisture accumulation will have a significant and more drastic effect than oxygen on the life of insulation [18].

### Stability of Furanic Compounds

Unlike carbon oxides, furanic compounds are specific to the degradation of cellulose paper. As they cannot be produced by oil degradation, they are used as an indirect measurement of the solid insulation condition. The five most common furans determined in oil analyses are the following:

- 2-furaldehyde (2-FAL)
- 2-furylalcohol (2-FUROL)
- 5-hydroxymethyl-2-furaldehyde (5HM-FAL)
- 2-acetyl furan (2A-FUR)
- 5-methyl-2-furfural (5M-FAL)

Of this group, 2-furfural is generally predominant and the most universally used insulating aging indicator.

However, there are some limitations in using furanic compounds as indicators because they are known to be sensitive to thermal and oxidative degradation. However there has been little reported on their stability at the range of temperatures experienced in an operating transformer or their relative affinity, after generated, for the oil or paper environment within the transformer.

To resolve some of these issues, Powertech Labs Inc. performed aging model tests on the following six furanic compounds in oil at two different temperatures (90 and 150°C) for eight weeks in the presence of air:

- 2-furaldehyde (2-FAL)
- 2-furylalcohol (2-FUROL)
- 5-hydroxymethyl-2-furaldehyde (5HM-FAL)

- 2-acetyl furan (2A-FUR)
- 5-methyl-2-furaldehyde (2M-FAL)
- 5-methyl-2 furfural (5M-FAL)

The following conclusions were drawn from these studies in our laboratory:

- With the exclusion of oxygen from the operating environment, all furans are stable at the most common range of 70 to 110°C.
- With the presence of significant quantities of oxygen in the operating environment, the rate of loss of furan concentration was in the following order: 2-FUROL > 5HM-FAL > 2-FAL > 5M-FAL > A-FUR. At 90°C, the loss is minimal for all furans except for 2-FUROL (see Figure 3-2). At temperatures above 110°C (see Figure 3-3), there is instability for some furans under favorable oxidative conditions.

Another report [19] suggested a relative stability of furanic compounds as indicated in Table 3-2.

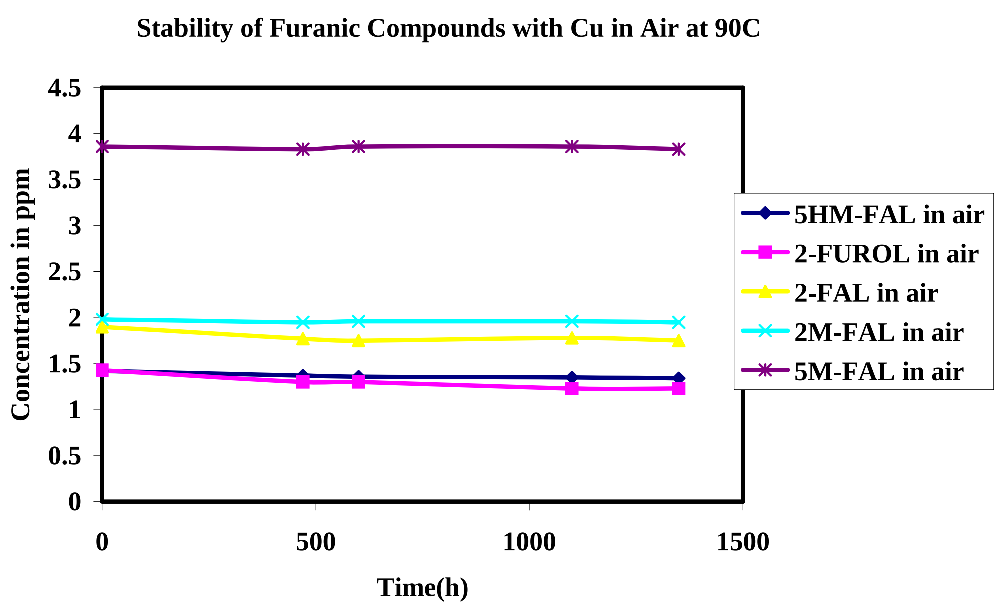


**Figure 3-2**
**Degradation of furanic compounds at 90°C monitored for eight weeks**

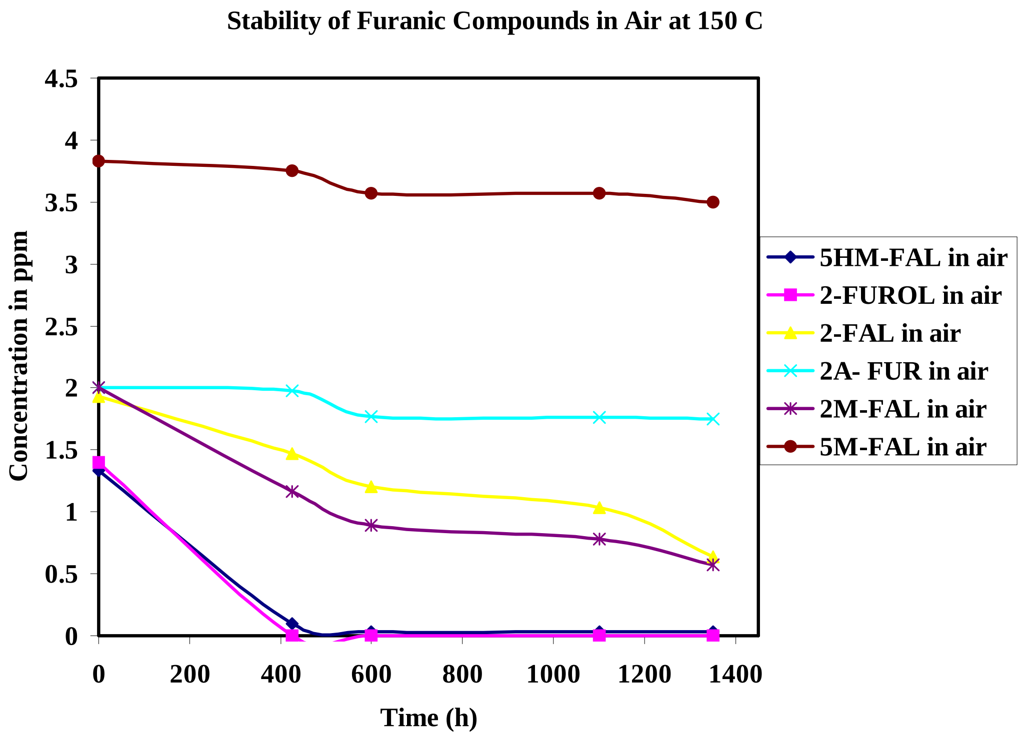


**Figure 3-3**
**Degradation of furanic compounds at 150°C monitored for eight weeks**

**Table 3-2**
**Relative stability of furan compound indicators at upper range of transformer operating temperatures under oxidation conditions, over two- and eight-week periods**

| Furan Type | Indicative Loss of Concentration After: | | | |
|---|---|---|---|---|
| | Two Weeks at 90°C | Eight Weeks at 90°C | Two Weeks at 110°C | Eight Weeks at 110°C |
| 2-FUROL | •• | ••• | ••• | ••• |
| 5M-FAL | • | •• | •• | ••• |
| 2-FAL | • | • | • | •• |
| 2M-FAL | — | — | — | • |
| 2A-FUR | — | — | — | • |

Key:
— Negligible loss (0–10%)
• Minor loss (10–20%)
•• Significant loss (20–40%)
••• Major loss (40–100%)

The rates of reaction and total changes measured in these experiments agree in essence with data presented by Griffin et al. [20] who showed that the alcohol is the least stable of all of the products. The decomposition rates are generally too low to account for the loss of 2-FAL observed experimentally during paper aging and most likely result from evaporation because the boiling points of furans are in the range of 160 to 200°C. It is important to note that it is quite rare that a transformer will run at such a high temperature (above 110°C).

## Partitioning with Paper

Furanic compounds are polar in nature and thus have a higher affinity for paper than for oil. As the load and temperature fluctuate, the furanic compounds will migrate between the paper and the oil as dictated by their partition coefficient. The partition coefficient is a measure of this affinity and defined as the ratio between the concentration of furans in paper (ppm) to that of the concentration of furans in oil (ppm). Dynamic partition between the paper and the oil will continue on a daily basis following the load cycles of the transformer.

Laboratory studies performed at Powertech Labs Inc. at 65°C gave a partition coefficient for 2-FAL between 3.5 and 5. Allan et al. [19] undertook further studies on the relative affinity of the furanic compounds for the oil or the paper within an operating unit. The laboratory trials gave the following partition coefficients (see Table 3-3) for each furan. These are comparable to the results obtained by Powertech Labs.

**Table 3-3**
**Relative affinity (partition coefficients) of furans for the oil or paper insulation**

| Furan Type | Partition Coefficient Paper/Oil | | |
|---|---|---|---|
| | 25°C | 70°C | 90°C |
| 2-FUROL | 33 | 12.5 | 25 |
| 5M-FAL | 0 | 0 | 0 |
| 2-FAL | 4.5 | 5.26 | 5.26 |
| 2M-FAL | 2.04 | 3.45 | 3.33 |
| 2A-FUR | 1.63 | 2.63 | 2.78 |

It is evident from these data that the bulk of the furan compounds in an operating transformer are within the paper insulation. The relatively rapid buildup of the concentration of 2-FAL in oil has been observed in actual transformers after an oil change (a memory effect). It is important to note that the partition coefficient is dependent not only on the temperature, but also on the different compounds present in the oil and/or paper. If there are more polar compounds on the paper, such as water, acids, aldehydes, ketones, and alcohols (obtained because of paper degradation), the partition coefficient may be affected.

## Effect of Thermally Upgraded Paper

Laboratory studies have shown that the amount of furanic compounds formed depends on the temperature as well as the type of paper used. As more data were gathered from the field on furanic compounds and $DP_v$ of insulating paper, more concerns arose on the usage of levels of furanic compounds to predict the end of life of a transformer. While it is not a firm rule, most 65° rise transformers manufactured in North America since approximately 1960 contain thermally upgraded paper in their windings. Thermal upgrading of the paper was commonly accomplished by impregnating the paper with the additive dicyandiamide (DICY).

Kelly et al. [25] compared furan formation from the aging of thermally upgraded paper and paper that had not been thermally upgraded (kraft paper). They also examined the stability of furanic compounds in oil spiked with dicyandiamide. Finally, a review of furanic compound concentration in two populations was undertaken. One population was primarily transformers that were manufactured with thermally upgraded paper; the other was a transformer with regular kraft paper. The conclusions drawn from this study were as follows:

- Thermally upgraded paper generated substantially lower concentrations of furanic compounds.
- Furanic compounds demonstrated lower stability in insulating liquids spiked with dicyandiamide.
- The population studies confirm the conclusions of the laboratory work. Furanic compounds, on average, were substantially higher in operating transformers that were manufactured using regular kraft paper.

Work performed at Powertech Labs Inc. also showed that the level of 2-FAL produced from thermally upgraded paper is substantially lower compared to regular kraft paper as shown in Figure 3-4. The reason for this is not clear, but it appears that the additive alters and slows down the decomposition mechanism. We have noted in laboratory studies that 2-FAL reacted with DICY to produce new non-furanic compounds. This may partly explain the lower levels of furans. In addition, laboratory studies performed only on windings with thermally upgraded paper showed a high concentration of 2-FUROL compared to 2-FAL. A ratio of 2:1 or higher was observed as shown in Figure 3-5. However, this is not observed in a real transformer with thermally upgraded paper on the windings because regular kraft paper and transformer boards are also present in the transformer. These types of papers produce more 2-FAL than 2-FUROL; therefore, the amount of 2-FUROL gets diluted and a ratio of 1:2 of 2-FUROL:2-FAL has been observed.

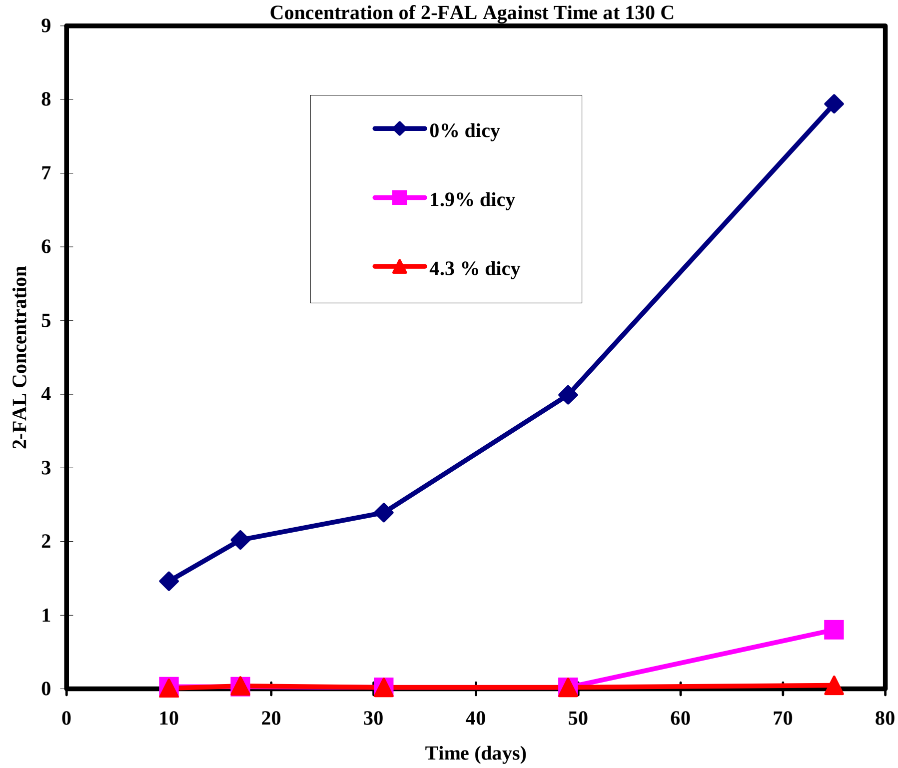


**Figure 3-4**
**Correlation between concentration of 2-FAL and type of paper used**

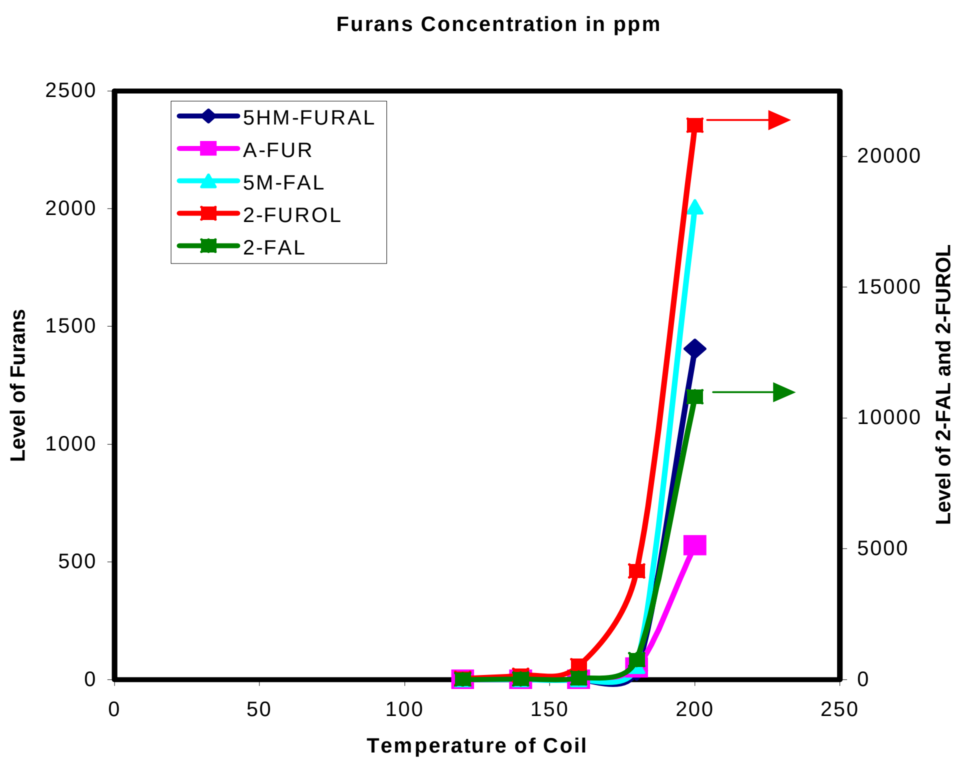


**Figure 3-5**
**Comparison of levels of furanic compounds produced at the windings**

## Correlation of Furanic Compound with $DP_v$

Many studies have been published establishing a relationship between the amounts of furanic compounds dissolved in the transformer oil and the condition of the solid insulation. Most studies show that a relationship between 2-FAL and the $DP_v$ of paper followed the log linear equation below, where k varies between -0.002 and -0.005 and C varies between 0.9 and 4.2, depending on the laboratory and the units used for the concentration of 2-FAL.

$$\text{Log } [\text{2-FAL}] = k \, DP_v + C$$

**Equation 3-3**
**Relationship between 2-FAL concentration and $DP_v$**

The use of 2-furaldehyde to determine the condition and the remaining life of paper is becoming widespread and part of routine oil analysis. By measuring the concentration of 2-FAL in the transformer oil, the $DP_v$ of the paper can be calculated or read off directly from a graph of empirical data of 2-FAL versus $DP_v$. If we assume that the remaining life of new paper is 100% and has a $DP_v$ of 1000 (values of 1200 have also been used) and that the end of life (0% remaining) is reached at a $DP_v$ of 200, the % remaining life, R (life), of paper is simply the ratio of the calculated (or measured) $DP_v$ to that of new paper minus its end-of-life value:

$$R \text{ (Life)} = [DP_v / (DP_{new} - 200)] \times 100$$

**Equation 3-4**
**Relationship between remaining life and $DP_v$**

Using this formula, the remaining life in terms of time may be calculated in the same way if we assume that aging proceeds the same way. The relationship between the $DP_v$ of paper and the 2-furaldehyde in the oil has been extensively explored by A. de Pablo [21], which contains the three well-known results from the Burton [22], Vuarchex and Chendong as described below [23]. Stebbins and S. D. Myers [24] later performed more work, which is included in Figure 3-6 for better comparison. The equations derived by each author are listed in Table 3-4 and are plotted in Figure 3-6.

**Table 3-4**
**Comparison of various models in predicting 2-FAL concentrations**

| Author | Equation Number | Equation | 2-FUR at DP 200 |
|---|---|---|---|
| Burton | 3-5 | $\text{Log}[\text{2-FAL}_{ppm}] = 2.5 - 0.005 \, DP_v$ | 31.62* |
| Vuarchex | 3-6 | $\text{Log}[\text{2-FAL}_{ppm}] = 2.6 - 0.0049 \, DP_v$ | 41.77* |
| Chendong | 3-7 | $\text{Log}[\text{2-FAL}_{ppm}] = 1.5 - 0.0035 \, DP_v$ | 6.30 |
| de Pablo | 3-8 | $DP_v ([\text{2-FAL}_{ppm}] + 2.3) = 1850$ | 6.95 |
| Stebbins | 3-9 | $\text{Log}[\text{2-FAL}_{ppm}] = 1.5655 - 0.0035 \, DP_v$ | 7.34 |
| Myers | 3-10 | $\text{Log}[\text{2-FAL}_{ppb}] = 4.17 - 0.00288 \, DP$ | 3.93 |
| Powertech | | $\text{Log}[\text{2-FAL}_{ppb}] = 4.38 - 0.0033 \, DP$ | 5.25 |
| | | | *Extrapolated |

From Figure 3-6, the following points are clear:

- The correlations from Burton and Vuarchex are similar but are above the others for higher 2-FAL concentrations.
- The correlations from Chendong, de Pablo, and Stebbins are similar at higher 2-FAL concentrations.
- The correlations of Chendong and Stebbins are very close to each other.
- The correlation obtained by S. D. Myers is lower than others for lower 2-FAL concentrations.

Figure 3-6 shows clearly that there are two groups of curves with some deviations; these data were obtained for two populations of transformers based on whether thermally upgraded paper has been used in the manufacture of the equipment. Except for the equations derived by Stebbins [25] and S. D. Myers [24], all of the other equations were derived from research on transformers using regular kraft paper.

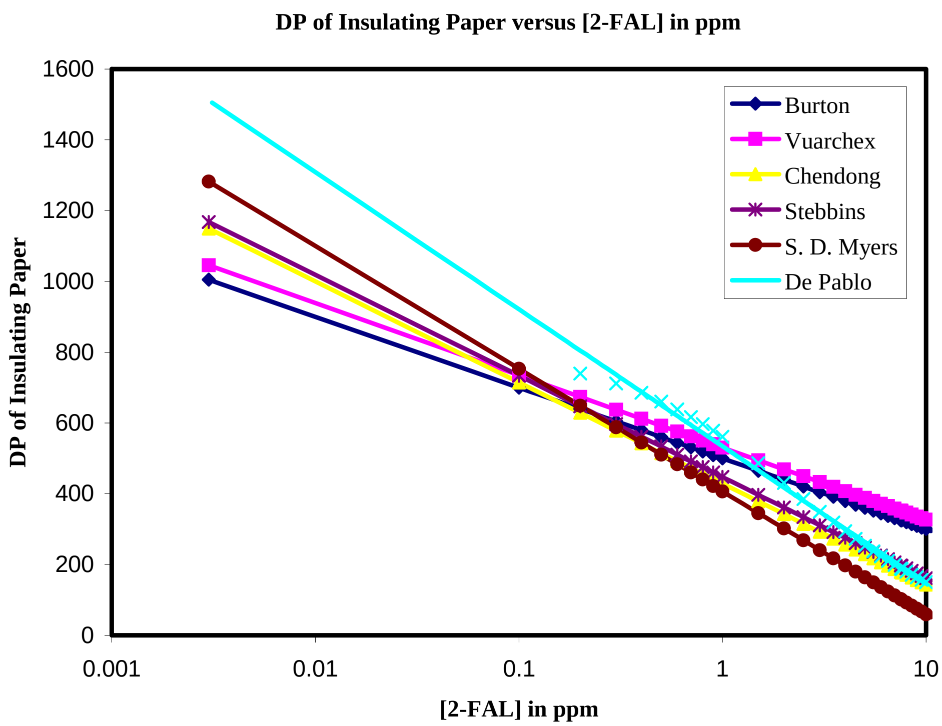


**Figure 3-6**
**Reported correlation between concentration of 2-FAL and $DP_v$**

Stebbins et al. [25] found that a model and an equation from a prior study provided the most reasonable approximation for $DP_v$ in transformers without thermally upgraded paper based on the level of furanic compounds that was found in operating transformers. Several laboratories use this technique, known as the *Chendong equation* [25]. It is important to point out that the correlation between furan content and $DP_v$ has been developed by the analysis of actual data from thousands of transformers in Europe, which in most cases do not contain thermally upgraded paper. Therefore, Stebbins et al. developed another model specifically for transformers with thermally upgraded paper. Subsequent studies with a transformer database for thermally upgraded insulation and regular kraft insulation supported the theory that the thermal upgrading chemicals react with the furans, breaking them down. Stebbins proposed a modified Chendong equation to be used for transformers with thermally upgraded paper.

In another study performed by Myers et al. [24], data on transformers with thermally upgraded paper (rated for a 65°C temperature rise) were collected. The samples were taken from transformers that were being scrapped or rewound. Paper for $DP_v$ testing was sampled from top windings, and oil was sampled for furan analysis. The best-fit data line (regression) has the equation as shown in Table 3-4 (Equation 3-10) with a correlation coefficient (r) for the graph being -0.85.

A statistical analysis was also performed at Powertech Labs Inc. to correlate the $DP_v$ of thermally upgraded paper to the level of 2-FAL; this is described in the next section.

## Comparison of Equations

It is interesting to compare the different models of the furan concentrations as described above. Plots of several models are given in Figure 3-6. All of the equations except Stebbins' and Myers' were based on experiments using regular kraft paper and/or on transformers with regular kraft paper. In addition, see Table 3-4 for a comparison of the predicted furan concentrations from various models at a $DP_v$ of 200, which is considered to be the end of life of a transformer. The prediction from Myers of 3.93 ppm of 2-FAL is lower than the prediction of every other model considered. The closest prediction to Myers is 60% higher at 6.30 ppm from the Chendong equation. As shown in Table 3-4, all of the models based on regular kraft paper—except for Stebbins' equation—predict higher 2-FAL concentrations at end of life than the model based on thermally upgraded paper.

As discussed earlier, it has also been reported that the DICY in thermally upgraded paper appears to degrade 2-FAL. Although Stebbins claims to have derived an equation that is reflective of degradation of thermally upgraded paper in a transformer, the concentration of 2-FAL at a $DP_v$ value of 200 is 7.34 ppm, which is higher than the value obtained from both Chendong and de Pablo's equation. This is in contrast with the other observations that thermally upgraded paper generates fewer furanic compounds than regular kraft paper.

From this literature review, it is observed that a 2-FUR concentration of approximately 4 ppm from a transformer containing thermally upgraded paper would probably indicate a problem, but if it were from regular kraft paper from a transformer, it might not be a great cause for concern. Therefore, when interpreting furan test results from transformers containing thermally upgraded paper, $DP_v$ predicting models based on regular kraft paper should not be used.

# 4

# STATISTICAL ANALYSIS

Statistical analysis was used in order to provide some validation to the correlations derived in laboratory experiments and published literature values. This type of analysis does not depend on extensive knowledge of transformer operating conditions. The information derived from this analysis has an inherent uncertainty and is valid only if the database is sufficiently large and statistically significant.

Powertech Labs Inc. stores all of the insulating oil test results from oil-filled equipment for BC Hydro (also called *BCGH*) and BCTC substations in a database called *LabsysV2*. This is a very large database, with historical results dating back approximately 20 years. All of the oil results for power transformer units were extracted from this database using Microsoft Access for queries, further analysis, graphing, and so on.

## Data Analysis

The results in this review represent the data collected from both BC Hydro and BCTC transformers containing mainly thermally upgraded paper. The furfural data were found to be quite scattered. Statistical distribution of furfural concentration in power transformers has been performed by many researches, and they commonly selectively eliminated some outliers before further analysis was carried out. In a previously reported paper [26], the furfural concentrations that are either too high (obviously indicating serious aging of the solid insulation or fault condition, a situation that has been confirmed by inspection) or too low (as low as the measurement precision) are excluded from the analyses.

In this review, the high and low concentrations of 2-FAL were not excluded. All of the values were included in the statistical distribution so that realistic warning levels of furfural in oil could be calculated more accurately than with truncated data. However, it is important to note that the high and low values obtained from the database were not that far from the average.

The percentile approach was used to plot the distribution of the transformers. In this method, as large a database population of similar transformers as possible is assembled, and the population values for 2-furaldehyde are charted as shown in Figure 4-1. From this graph, it is possible to calculate the percentage of overall population of similar units in the database that fall below and above this value. This method has been used for several years by IEC and other researchers with significant success.

From the data analysis of the transformers from BCTC and BC Hydro, a difference in the percentile was observed between transformers with thermally upgraded paper and those with regular kraft paper, as shown in Figures 4-1 and 4-2. The amount of 2-FAL produced from the regular kraft paper is nearly twice the amount produced in transformers with thermally upgraded paper. And as shown in Tables A-1 and A-2, the 98th percentile for transformers with thermally upgraded paper is calculated at 1.04 ppm of 2-FAL and that with regular kraft paper at 1.709 ppm.

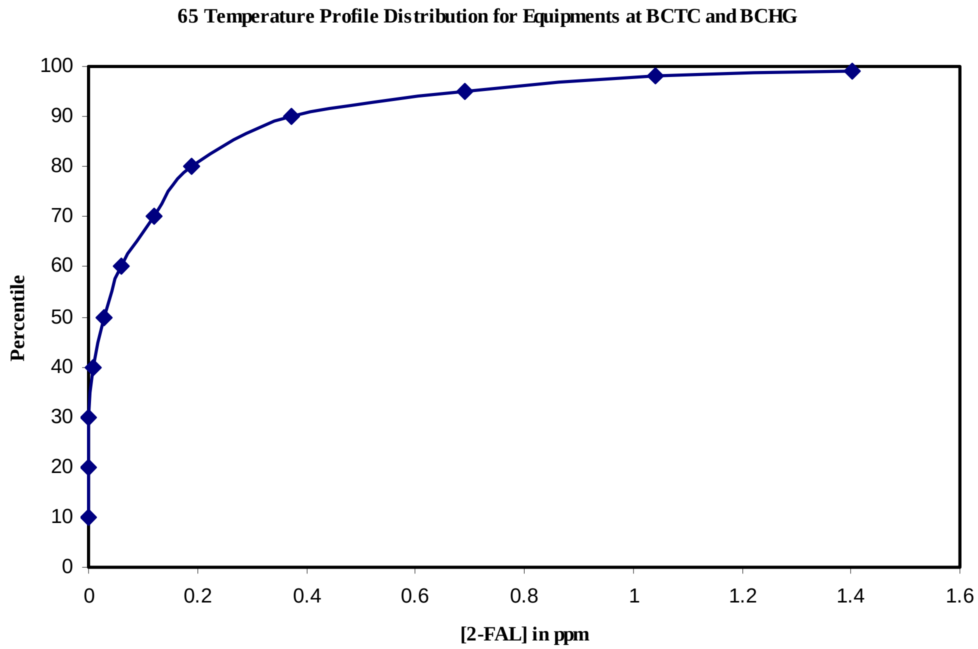


**Figure 4-1**
**Distribution of 2-FAL concentrations for 65°C temperature rise transformers at BC Hydro and British Columbia Transmission Corporation**

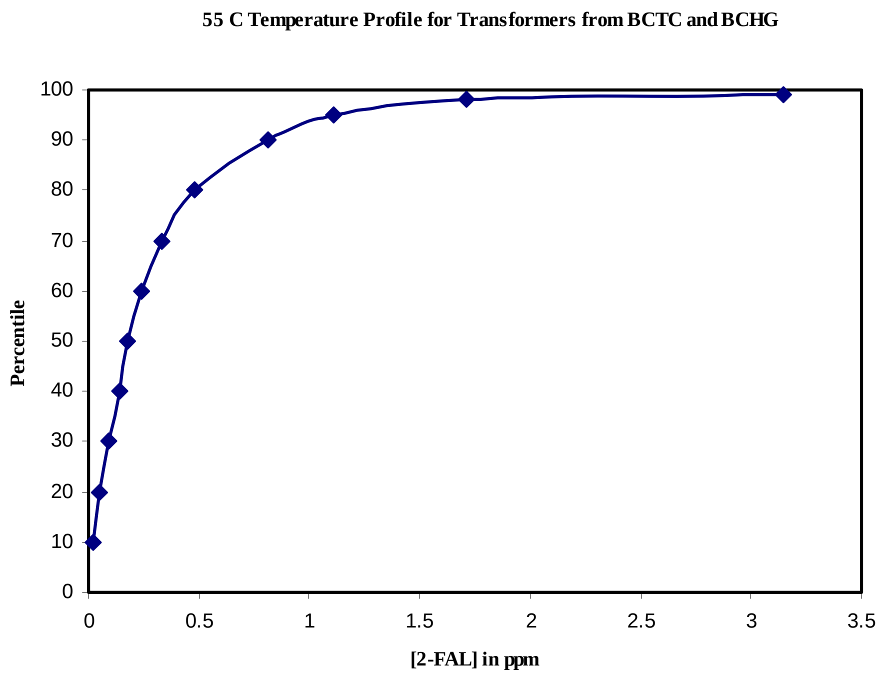


**Figure 4-2**
**Distribution of 2-FAL concentrations for 55°C temperature rise transformers at BC Hydro and British Columbia Transmission Corporation**

A distinct difference is also observed in the ratio of 2-FUROL:2-FAL from transformers containing thermally upgraded paper to regular kraft paper as shown in Figure 4-3. It was found that for thermally upgraded paper, twice the amount of 2-FUROL is obtained compared to regular kraft paper. The caution level (90th percentile) ratio for a transformer with regular kraft paper is 0.1 and that with thermally upgraded paper is 0.2.

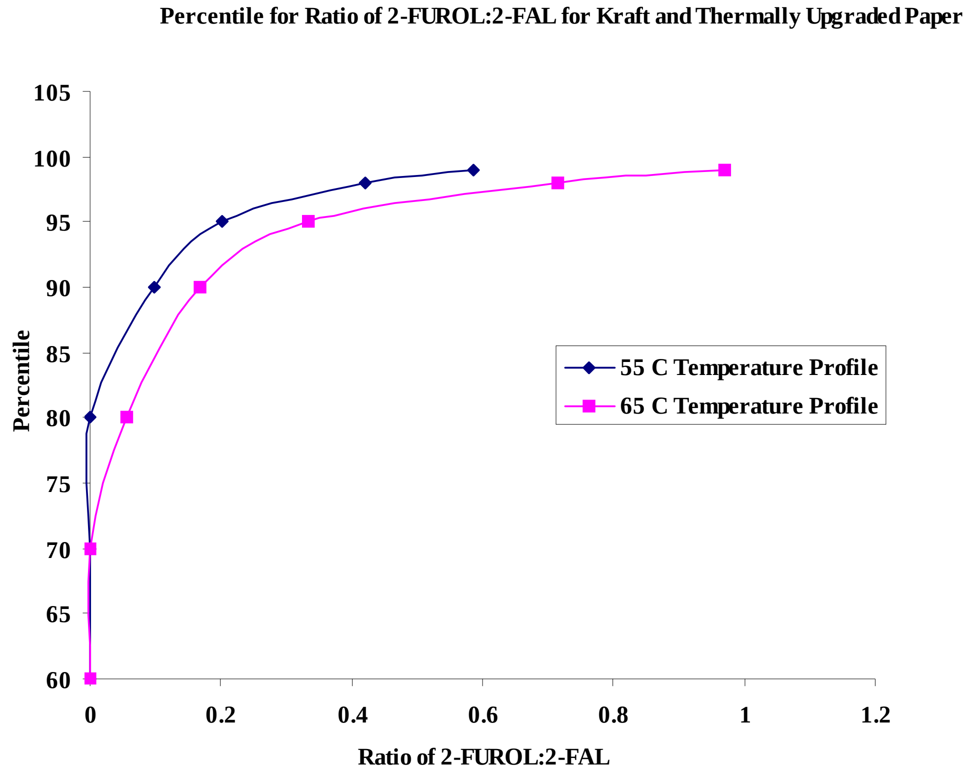


**Figure 4-3**
**Ratio of 2-FUROL to 2-FAL for thermally upgraded paper and kraft paper**

## Interpretation of 2-FAL Test Results

With almost 3100 test results, it is possible to take an actuarial approach. However, one should be very careful when using this approach because there are many confounding factors. For example, one should never make critical decisions on the basis of a single furan test result. Several test results over a period of months are needed. In addition, all other available test results, especially dissolved combustible gases, should be considered. Nameplate information must also be factored into any decisions. If furans are high in a young transformer, some type of incipient fault is likely. In an old or overloaded transformer, high furans may be the result of deterioration with time or paper aging.

## Correlation Curves

In this study, furan results and paper DP data of transformers from BCTC and BC Hydro with thermally upgraded paper were collected (rated 65°C temperature rise). Paper samples were taken from different locations of the transformers, and their $DP_v$ was plotted against 2-FAL in oil. The data pooled to date are from 18 different transformers and are shown in Figure 4-4. The scatter of DP values reflects different values from different locations, and the solid line represents the best fit (regression) in Equation 4-1:

$$DP_v = -303.03 \text{ Log } [2\text{-FAL}_{ppb}] + 1327.303$$

**Equation 4-1**
**Powertech Labs equation for the relationship between $DP_v$ of transformers with thermally upgraded paper and 2-FAL concentrations**

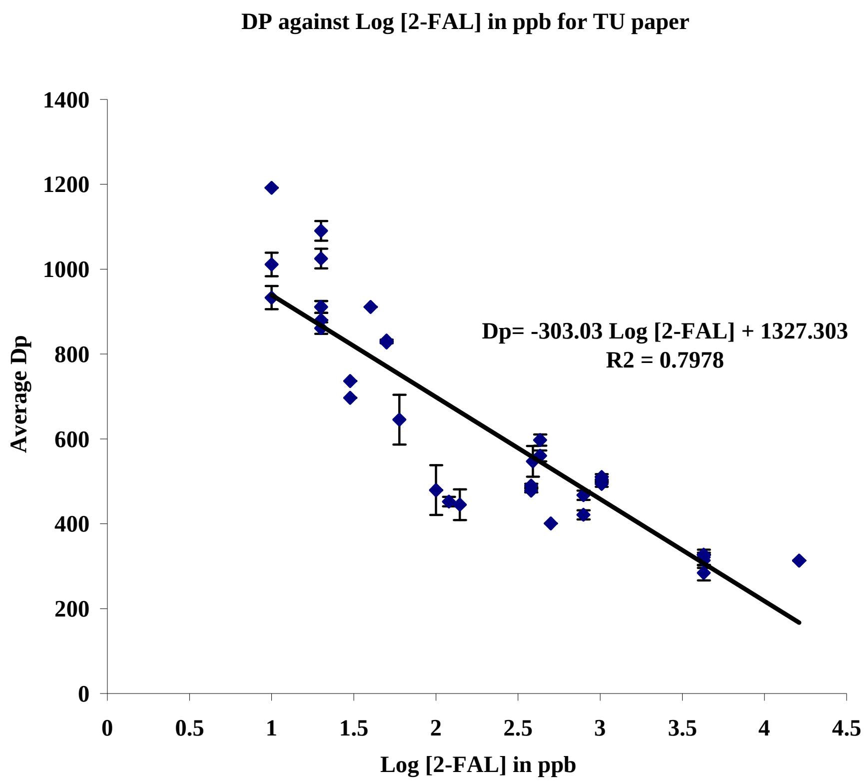


**Figure 4-4**
**Relationship between $Log_{10}$ 2-FAL (ppb) in oil and $DP_v$ of thermally upgraded paper**

The correlation coefficient ($R^2$) for the graph is 0.7978. In comparison to other correlations reported in the literature, the concentration of 2-FAL for a $DP_v$ of 200 is 5.25 ppm. This value lies between the value obtained by Stebbins (7.34 ppm) and Myers (3.93 ppm) as shown in Figure 4-5.

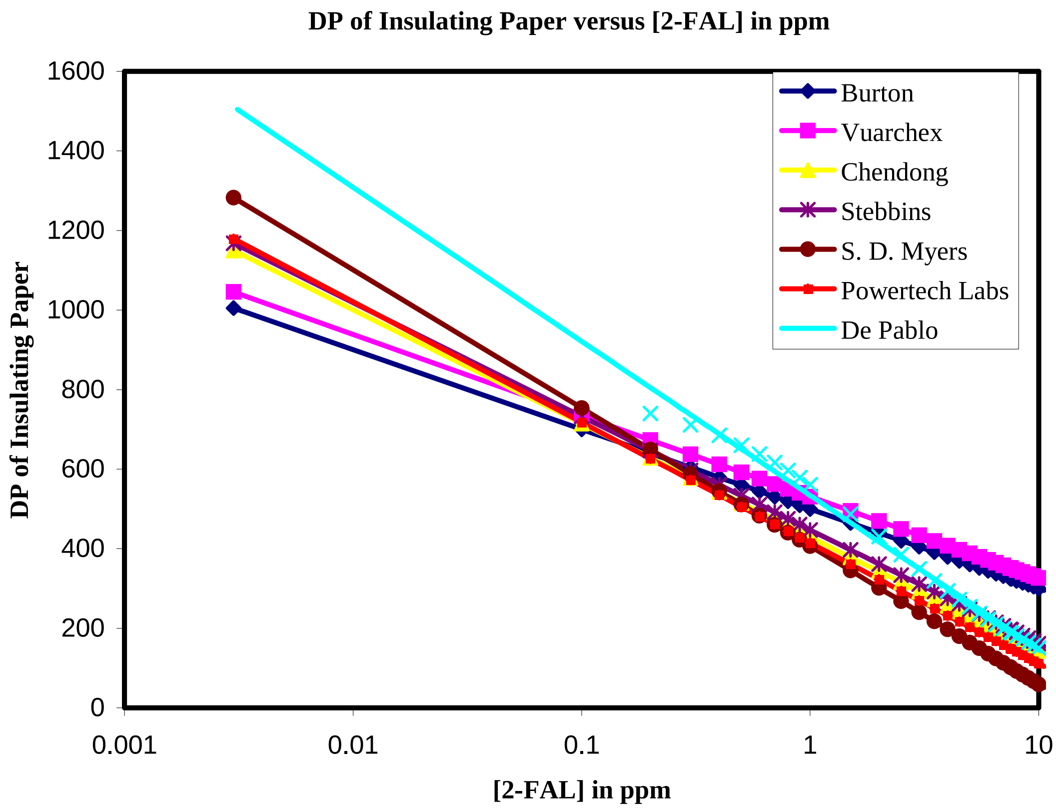


**Figure 4-5**
**Comparison of curves relating 2-FAL concentrations to $DP_v$ of insulating paper**

It is important to note that in Figure 4-4, the value for 2-FAL relates to the average value of $DP_v$ for the entire insulation system. As expected, there are pronounced temperature gradients between the top and the bottom of a transformer, resulting in lower $DP_v$ at the top and higher $DP_v$ at the bottom. However, other factors such as moisture content of the paper may also affect the $DP_v$ at these locations. From the $DP_v$ data obtained from transformers at BC Hydro, the lowest $DP_v$ values were found on the winding conductors near the top of the transformer. A variation between 15 and 30% was observed between the top windings and the bottom windings. At higher concentrations of 2-FAL, a higher gap between the $DP_v$ was observed. Therefore, when estimating the $DP_v$ of the windings while using the concentration of 2-FAL from the oil, it is important to remember that the $DP_v$ at the top winding will be lower than the average as calculated by 2-FAL—and can be as much as 30% lower than the one at the bottom.

## Actuarial Approach

Usually the high furan levels obtained from laboratory experiments are scarce. One explanation is that the high-furan transformers have brittle paper and are prone to failure—and because all of the transformers considered for this review were operating transformers, the failed units were excluded for this study. Other explanations for the observed concentrations of furanic compounds are possible, however. Perhaps the observed distribution reflects the stability of the furanic compounds themselves over long periods and in the presence of oxygen. Some compounds might be too unstable to build up to high concentrations as explained in Section 3. However, for 2-furfuraldehyde, instability does not seem to be a major issue, and 2-furfuraldehyde was the dominant compound found in most of the transformers tested. In addition, there were only a few transformers with levels of 2-FUR above 5000 ppb.

Usually we would expect one to have many years of furan data, beginning with the time the transformer was first energized and extending to and past the time of the eventual failure. However, this is not the case; therefore, one must approximate the life remaining in a transformer from its percentile in the furan population. The furan data for the entire population of transformers are analogous to the life cycle of a single unit because each unit is at a different stage in its life cycle. From the BCTC and BC Hydro database, the relationship between the $DP_v$ of transformers containing thermally upgraded paper at the windings and the level of 2-FAL was derived as shown in Figure 4-6. The relationship follows Equation 4-1 with a standard deviation of ±50 $DP_v$. Therefore, after the 2-FAL concentrations are measured from the oil using high-performance liquid chromatography (HPLC), the average $DP_v$ of the windings can be estimated.

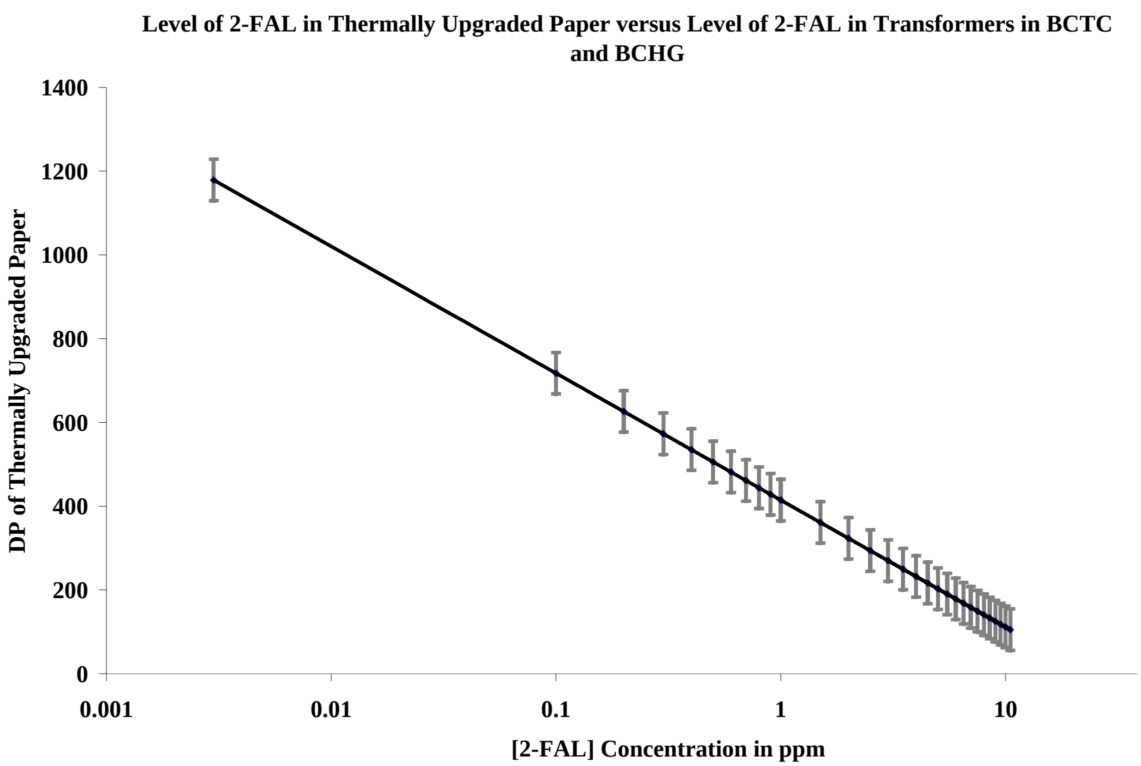


**Figure 4-6**
**Relationship between 2-FAL concentration and $DP_v$ of thermally upgraded paper in transformers at BCTC and BCHG**

After the average $DP_v$ is estimated from Figure 4-6, the remaining life of the transformer can be projected using Figure 4-7. Note that to determine the relationship between $DP_v$ and the remaining life of a transformer, an expected lifespan for the transformer must be assumed. In our example, we have taken it to be 20 years with the end-of-life $DP_v$ set at 200 and new $DP_v$ at 1000. Although one cannot predict the exact date and time of a failure for a specific transformer, one can estimate the probability of failure. This calculated value should be used only as an estimate and is more useful for ranking similar transformers than for determining actual remaining life.

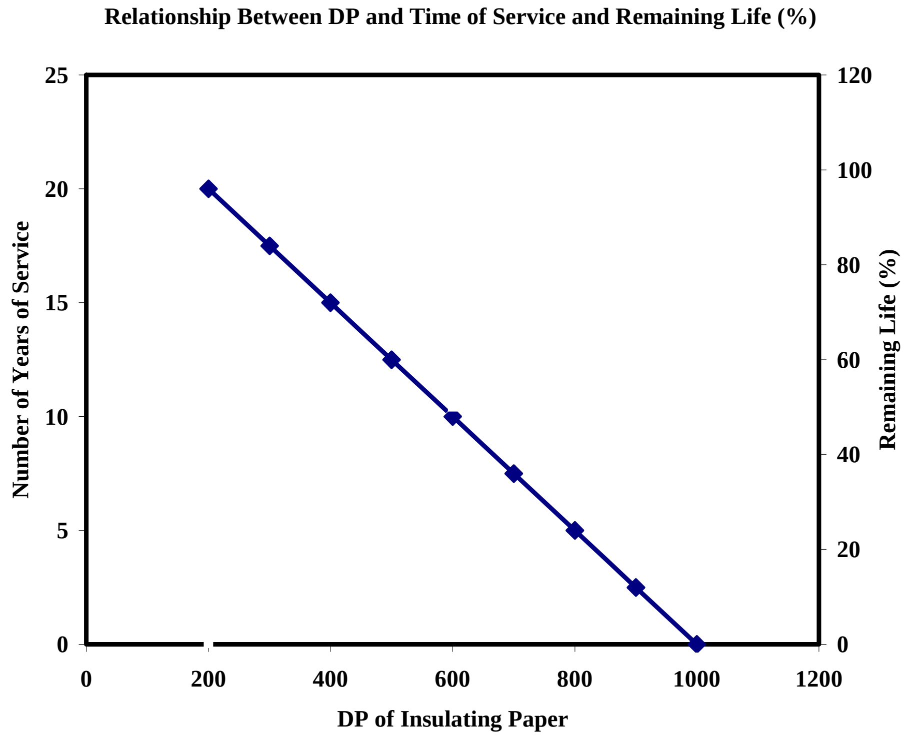


**Figure 4-7**
**Relationship between $DP_v$, time of service, and remaining life of transformer**

## Percentile Score Approach

A comparison of the percentage life used, calculated as above to an average of the measured $DP_v$, is shown in Table 4-1. This was achieved from the measured furanic compound content of in-service transformers from both BCTC and BC Hydro. The "percent life used by mean $DP_v$" was calculated using the average measured $DP_v$ (which includes values from different sections of the transformer) compared to the initial value of 1000 and the end-of-life definition of 200.

**Table 4-1**
**Comparison of actuarial life remaining to life remaining as calculated by $DP_v$**

| | Unit 1 | Unit 2 | Unit 3 |
|---|---|---|---|
| Measured mean DP | 577 | 422 | 252 |
| % Life used by mean DP | 52.9 | 72.3 | 93.5 |
| 2-FAL in ppb | 140 | 230 | 1060 |
| % Life used from furan result | 58.5 | 76.0 | 95.5 |

For example, Equation 4-2 shows the calculation of percent life used by mean $DP_v$:

$$\% \text{ Life Used} = \{(1000 - \text{Average } DP_v)/800\} \times 100$$

**Equation 4-2**
**Equation for percent life used**

In this example, the percent life used was overstated by furanic compound analysis compared to $DP_v$ measurement by 5.6%, 3.7%, and 2.0%, respectively. This is fairly typical and also acceptable to be biased in this direction, as the difference is almost always conservative. By overstating life used in this fashion, interpretations are biased toward preventing unplanned or unscheduled outages.

## Conclusion for the Percentile Approach

The furan test provides a quantitative benchmark for decisions on prioritizing the retirement of transformers. For easy comparison with the more traditional $DP_v$ test, the $DP_v$ ranges equivalent to the "percent life remaining" furan ranges were computed from the following formula. Recall that the new transformer paper has a $DP_v$ of 1000 and that the end-of-life is defined as the $DP_v$ of 200.

$$\% \text{ Life remaining} = 100(DP_v - 200)/(1000 - 200)$$

**Equation 4-3**
**Equation of percent life remaining**

The percent life from the actuarial approach is equated to the percent life from the $DP_v$ equation. The percent life from the furanic compounds was found to overstate the $DP_v$ measurement by nearly 3%. We observed the following from 2-FAL concentration and thresholds from our database and experience:

- Transformers with a 65°C rise (containing thermally upgraded paper around the windings) produce a lower level of 2-FAL and a higher level of 2-FUROL compared to transformers with a 55°C rise.
- The caution level (90th percentile) for transformers with regular kraft paper is 0.8 ppm of 2-FAL and, for transformers with thermally upgraded paper, the caution level is 0.373 ppm.
- The caution ratio of 2-FUROL:2-FAL (90th percentile) for transformers with thermally upgraded paper is 0.2 and for transformers with regular kraft paper is 0.1.

# 5
# THE ALGORITHM

At the moment, there are no industry standards for acceptable threshold levels for furanic compounds. In this study, the percentile method is being used to determine the levels and severity of the faults in the transformers. The percentile values are calculated from the database of oil results of transformers from BC Hydro and BCTC. It is based on the premise that an abnormal condition will manifest itself in abnormally high or low test results. Statistically, it is generally accepted that 90% of the values fall in the normal range. Values greater than the 90th percentile are considered suspect and should be investigated further. If we anticipate a 2% failure rate, values greater than the 98th percentile are considered to be in a pre-fault mode. The recommended actions based on the percentile criteria levels are shown in Table 5-1.

**Table 5-1**
**Conditions and recommended actions for percentiles**

| Percentile | Condition | Recommended Action |
|---|---|---|
| <90 | Normal | Continue normal operation and sampling frequency. |
| 90 to 95 | Caution | Monitor change and increase sampling frequency. |
| 95 to 98 | Warning | Operate with caution, resample, and plan inspection. |
| >98 | Alarm | Internal inspection is recommended. |

Based on our transformer database, we have calculated generic 90th, 95th, and 98th percentiles to use as threshold levels. These values are listed in Tables A-1 and A-2 and should be used only as a guide because actual values may vary based on each utility's age of equipment and operating practice. In addition, whenever possible, historical results should be reviewed to see if there have been sudden changes because these may be an indication of a developing problem.

## Details of Algorithm

Interpretation of the oil analysis results required the examination of several parameters to determine whether a fault is indicated and its severity. The algorithm is meant to be used only as a guide, and it is recognized that not all factors can be taken into account. The factors that were, however, taken into consideration are as follows:

- Concentration of furanic compounds in oil
- Temperature rating of the transformer
- Oil exchange or reclamation
- Ratio of 2-FUROL to 2-FAL
- Rate of formation of 2-FAL and 2-FUROL

The approach taken in arriving at an interpretation guide is outlined in the steps below, and the logic tree used is shown in Figure 5-1.

### *Step 1: Sampling and Analysis*

It is critical that proper sampling procedures are followed, as this will determine the reliability of the results. If in doubt, one should follow the same ASTM procedure for sampling transformers for DGA analysis. Along with the oil sample should be equipment nameplate information and sampling details, including temperature at the time of sampling.

Similarly, the analysis should be done by a reputable, competent laboratory and in accordance with ASTM or IEC procedures. Typical analysis should give results for five furanic compounds (2-furaldehyde, furyl alcohol, 5-hydroxy furaldehyde, 5-methyl furaldehyde, and acetyl furaldehyde). In addition to these, some labs also analyze for phenols and cresols to assist with the diagnosis and location of the fault.

### *Step 2: Normalizing Results*

Migration of furanic compounds from the paper to the oil is a function of the bulk oil temperature and to a lesser extent the moisture content of the paper. Theoretically, if the temperature at the time of sampling is known, one could correct the results to a standard temperature. To do this, we must have partition coefficients for each compound as a function of temperature. At present, no such reliable functions exist and thus no correction can be made. The same applies to the effect of moisture in paper.

In addition, the results should be adjusted for the volume of oil in the transformer. A larger volume of oil in a transformer will give a lower concentration of furanic compounds as there will be a larger dilution. This variation may not be significant for most modern transformers of similar rating but may be for older units with different design tolerances. For adjustment to be meaningful, we must also know the amount of paper in the system. However, as this information is not readily available, we will not take it into account for the time being. As the data become more refined, they can then be included in the calculations.

### *Step 3: Correcting for Operating Conditions*

Operating conditions that affect the production of furanic compounds—such as temperature, moisture, and oxygen content—are reflected in the levels of furans in oil, and no correction is necessary. The presence of furanic compounds in oil is a cumulative process and should increase with time. A decrease in their levels with time may be observed, but this does not reflect an improvement in the condition of the paper because its degradation is irreversible. Thus the highest historical results for furans should be used for determining the $DP_v$ of paper. If the oil was exchanged or reclaimed with Fuller's earth or similar adsorbent, the furans are removed in the process, and the highest result before reclamation should be selected.

If the oil was reclaimed and no prior result (within six months) is available, a correction can be made for a result following oil reclamation. As described previously, most of the furanic compounds remain in the paper and will leach back into the oil in time. A new paper-oil equilibrium will be reached within two to six months. The exact furanic levels in the oil will depend primarily on the temperature of the bulk oil. Our calculations, based on partition coefficients at 70°C, indicated that the system would re-equilibrate at 67% of the original value. Thus the furanic results in oil measured four to six months after oil reclamation should be multiplied by a factor of 1.5. To be sure that equilibration has occurred, an oil sample should be taken after six months of reclamation.

### *Step 4: Calculating Condition and Loss of Life*

At this point, the $DP_v$ of the paper can be calculated using the value obtained for the level of 2-FAL. Because kraft and thermally upgraded paper age at different rates, it is necessary to use two distinct equations for this step. For a 65°C rise transformer (thermally upgraded paper), we use Equation 4-1; for a 55°C rise transformer, we use Equation 5-1. The loss of life and remaining life can be calculated using Table A-3.

$$DP_v = -285.7 \text{ Log } [\text{2-FAL}_{\text{in ppm}}] + 428.6$$

**Equation 5-1**
**Rearranged Chendong's Equation**

### *Step 5: Determining Presence of Fault*

The levels of 2-FAL and 2-FUROL are compared to threshold levels to determine whether further action is needed and if a potential fault is indicated. Again, two distinct tables are used for this: Table A-1 for a 65°C rise and Table A-2 for a 55°C rise (or undetermined) transformer. If the 90th percentile has not been exceeded by either of the two furanic compounds, the transformer is deemed to be operating normally and no further action is required. If the 90th percentile has been exceeded, further action should be taken as indicated in Table 5-1.

### *Step 6: Determining Location of Fault*

Fault location is difficult to determine, however. As discussed earlier, thermally upgraded paper produces more 2-FUROL than 2-FAL. The ratio of 2-FUROL to 2-FAL relates to the overheating problem of thermally upgraded paper. Thus if the fault is in the windings of a thermally upgraded transformer, the ratio of 2-FUROL to 2-FAL should be higher than normal. If it is lower than 0.2, there is a possibility for the presence of a general overheating problem. However, if the value is greater than 0.2, the possibility of a winding fault is indicated. The ratio 0.2 has been obtained from statistical analysis of the ratio of 2-FUROL to 2-FAL from transformers from BC Hydro and BCTC, and it was observed that the 90th percentile of this ratio was around 0.2.

### *Step 7: Determining Fault Activity*

Under normal operating conditions, paper degrades slowly, and low levels of furanic compounds form and accumulate in the oil. If we assume that a transformer takes 20 years to reach its end of life at a $DP_v$ of 200, the rate of accumulation of 2-FAL for a 65°C rise transformer has been estimated at 200 ppb per year and, for a 55°C rise transformer, 400 ppb per year. If we assume that the transformer will reach its end of life in 40 years, these values will be halved. When these rates are exceeded, an active fault may be indicated. Similar calculations can be done using 2-FUROL. The rate of accumulation for 2-FUROL for a 65°C rise transformer has been estimated to be 50 ppb per year and, for a 55°C rise transformer, 25 ppb per year for a 20-year estimated end of life—and half of these for a 40-year end of life. An active fault may be indicated if these specified levels are exceeded.

### *Step 8: Determining Sampling Interval and Actions*

The last step is to determine the progression or severity of the fault. Normally, this is done by calculating the rate of generation of 2-FAL and 2-FUROL separately from two most recent consecutive analyses using the following equation:

R = (Latest Result - Previous Result)/Elapsed Time

After this is done, we can determine the time to reach the alarm levels (98th percentile) separately for 2-FAl and 2-FUROL as follows:

$t_a$ (Time to alarm) = (alarm level – present level)/R

The shorter the time interval, the more severe the fault and the shorter the time interval for the next sampling should be. To determine the next sample time, the time to alarm is compared to the time remaining to the next scheduled sample ($t_s$). If $t_a$ is greater than $t_s$, the next sample is taken at the regular scheduled time. If $t_a$ is less than $t_s$, the next sample should be taken at half the time to the time to alarm. However, if the time to alarm is very short—on the order of one or two months—immediate action should be considered. This should include re-sampling for DGA, reducing the load, and shutting it down for an inspection if necessary.

The flow diagram for the algorithm is shown in Figure 5-1.

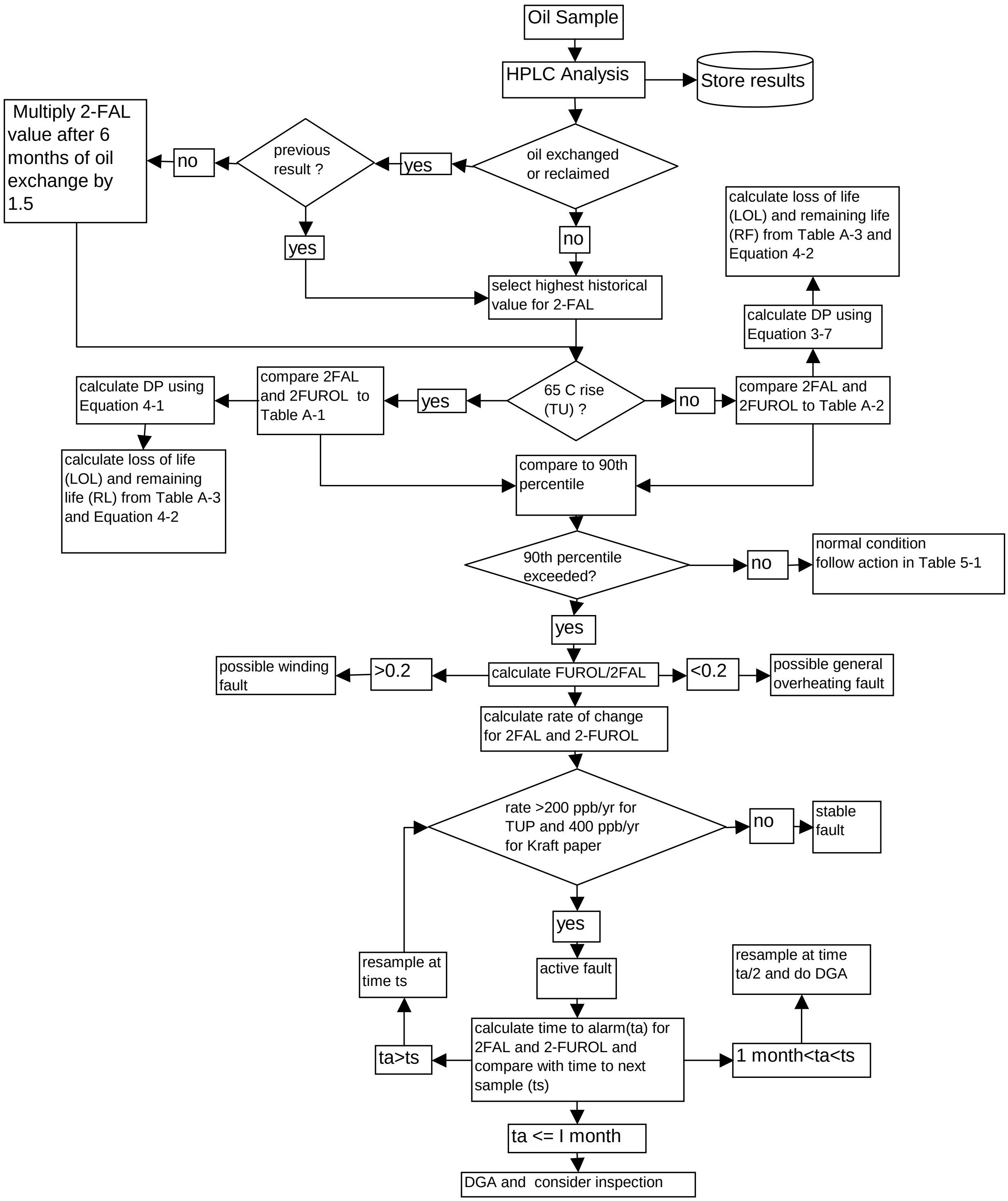


**Figure 5-1**
**Transformer algorithm flow diagram**

# 6
# CONCLUSION AND RECOMMENDATIONS

## Conclusion

Thermally upgraded paper behaves differently from kraft paper insulation in its aging characteristics and the by-products that are formed. The concentrations of furanic compounds detected are generally lower for transformers with thermally upgraded paper commonly used in North America. As a result, different correlations exist between the 2-FAL level of the oil and the $DP_v$ of paper in transformers. Thus separate equations must be used to estimate the $DP_v$ of paper, loss of life, and remaining life of these transformers. These equations were derived from previous work carried out at Powertech Labs and from published literature values.

In applying the measured 2-FAL levels from oil for condition assessment and diagnostics, several parameters must be taken into account. Of critical importance is the type of insulation paper used in the transformer. Other parameters include operating and maintenance history, oil temperature at the time of sampling, rate of formation of furanic compounds, and their relative ratio. With these parameters taken into account, an algorithm was developed to assist maintenance engineers in determining the condition of the paper insulation; the presence, location, and severity of an incipient fault in the paper; and recommended actions to take.

Statistical analysis from a large database at Powertech Labs showed good correlations between $DP_v$ and the level of 2-FAL for 65°C rise transformers and was in close agreement with published values.

Values of 2-FAL >1.7 ppm for transformers with regular kraft paper and 2-FAL level >1.0 ppm for transformers with thermally upgraded paper indicate advanced paper degradation and require further action to determine the presence of an incipient fault.

## Recommendations

Although considerable work has been done to relate furanic compounds in oil with the condition of the paper insulation, there remain several areas where improvement is needed. Consequently, the following recommendations are made:

- Expand the database of results from operational transformers to establish or improve the correlations of furanic compounds to the $DP_v$ of paper and incipient fault with the following:
  - Manufacturer, model, and rating
  - Transformer designs (core or shell) and oil volume
  - Top or bulk oil temperature
  - Conservator type, moisture, and oxygen content
  - Normal fault patterns and rates of production

- Continue research to determine the presence of other marker compounds better suited for condition assessment and diagnostics of thermally upgraded kraft paper transformers.
- Continue research to establish a correlation between ratios of furanic compounds and the temperature of paper decomposition. This will allow us to distinguish between a small but dangerous high-temperature hot spot in the windings and a large, less harmful lower temperature problem.

# 7
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# A
# THRESHOLD LEVELS BASED ON STATISTICAL ANALYSIS

Tables A-1 and A-2 present calculated generic 90th, 95th, and 98th percentiles to use as threshold levels.

**Table A-1**
**Percentiles of 2-FAL and 2-FUROL concentrations for transformers of 65°C temperature profile**

| Percentile | Level | Dissolved 2-FAL concentration in ppm | Dissolved 2-FUROL concentration in ppm |
|---|---|---|---|
| <90th | Normal | <0.373 | <0.030 |
| 95th | Caution | 0.690 | 0.090 |
| 98th | Warning | 1.040 | 0.216 |
| >98th | Alarm | >1.040 | >0.216 |

**Table A-2**
**Percentiles of 2-FAL and 2-FUROL concentrations for 55°C rise (or unknown) transformers**

| Percentile | Level | Dissolved 2-FAL Concentration in ppm | Dissolved 2-FUROL Concentration in ppm |
|---|---|---|---|
| <90th | Normal | <0.800 | <0.030 |
| 95th | Caution | 1.109 | 0.070 |
| 98th | Warning | 1.709 | 0.133 |
| >98th | Alarm | >1.709 | >0.133 |

The data in Table A-3 can be used to calculate the loss of life and remaining life.

**Table A-3**
**Calculate remaining life of a transformer with a 20-year life expectancy**

| $DP_v$ Reading | Time of Service | Remaining Life |
|---|---|---|
| 200 | 20 | 0 |
| 300 | 17.5 | 12.5 |
| 400 | 15 | 25 |
| 500 | 12.5 | 37.5 |
| 600 | 10 | 50 |
| 700 | 7.5 | 62.5 |
| 800 | 5 | 75 |
| 900 | 2.5 | 87.5 |
| 1000 | 0 | 100 |

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