“PRACTICAL EXPERIENCE GAINED FROM FURANIC COMPOUND ANALYSIS”

by Lance R. Lewand, Doble Engineering Company

When cellulosic materials are heated above 100°C, they begin to generate characteristic degradation byproducts, some of which are oil-soluble. These can be sampled easily and used as indicators of aging. These types of tests are known as “indirect tests,” since they are not direct measurements on the paper. There are two kinds of indirect tests for determination of cellulose degradation: dissolved gases-in-oil; and furanic compounds-in-oil. This article focuses on the latter: furanic compounds in oil. (For a more detailed discussion of furanic compound analysis, go to www.doble.com, and choose “Featured Paper.”).

Furanic compound analysis has been used for close to twenty years to help diagnose cellulosic insulation in dielectric liquid-filled electrical equipment. Yet, it is not as well understood as dissolved gas-in-oil analysis (DGA), nor are the factors that influence the generation, degradation, and accumulation of furanic compounds.

This article explores factors affecting the degradation of paper insulation such as temperature, water, and oxygen, as well asd the general patterns often seen in transformers that have not had internal maintenance that would alter the amount of furanic compounds.

Mineral oil, paper and other cellulosic materials such as pressboard and wood are the primary components of the transformer insulation system. These insulating materials have been selected because of the following qualities: 1) abundance resulting in low cost, and 2) reasonable longevity under normal operating conditions. However, these materials will degrade over time and therefore have a finite life. As a result, the life of the solid insulating materials is directly related to the life of the transformer. Because of this great emphasis has been placed on estimating residual insulation life in transformers.

DEGRADATION OF PAPER INSULATION

Thermal stress and the concentration of water and oxygen influence the degradation rate of insulating materials. The most critical component of the insulation system is the paper intimately wound around the copper or aluminum conductors in the windings and therefore not easily replaced. Good quality mineral insulating oil is expected to last 30 or more years before forming excessive amounts of acids and sludge. Although important, is not as critical as the cellulosic insulation because it is easily reconditioned to remove water and particles, reclaimed to remove degradation products or replaced. Therefore, the longevity of cellulosic materials, becomes the limiting factor in the operation of transformers [See: Lewand L.R. and Griffin P.J., “How to Reduce the Rate of Aging in Transformer Insulation”, *NETA World*, Spring, 1995.].

As paper and other cellulosic materials deteriorate, byproducts such as carbon oxide gases (carbon monoxide and carbon dioxide) gases and furanic compounds are formed. These compounds can serve as indicators to act assess the aging process. The degradation of cellulosic materials can also be measured directly by the degree of polymerization (DP) test. Before discussing the relative merits of each of the tests, it is useful to review aging factors and the chemistry of cellulosic materials, deterioration processes, and byproduct formation.

AGING FACTORS OF CELLULOSE INSULATION:

The effects of temperature, water, and oxygen are significant factors in the aging of the paper insulation (cellulose) and oil. Aging processes have been explored extensively through accelerated aging tests and field experience. A general discussion of the effects of aging factors on paper insulation is provided.

Effects of Temperature:

In general it can be stated that the primary cause of deterioration of paper is from thermal instability. Thermally-upgraded paper is less sensitive than Kraft when exposed to excessive temperatures. As Mr. W. J. McNutt discussed in his paper, [McNutt, W. J. "Insulation Thermal Life Considerations For Transformer Loading Guides", IEEE Trans. on Power Delivery, Vol. 7, No. 1, Jan. 1992, Pg. 392-401.] the aging of the paper insulation follows Arrhenius type-kinetics. Although he expressed the effects of temperature on aging with an equation, a rough index is that for every 6 to 8°C rise in temperature, the life of the paper insulation is halved.

Of course, the temperature at which you begin is important. For instance, using Mr. McNutt's equation, if the operating temperature of the insulation is 40°C, the life of that insulation is approximated at 110,000 years. However, if this same insulation is exposed to a temperature of 140°C the estimated life is now only about one year.

Effects of Water:

The effect of water on the aging of paper is significant and deleterious. The rate of paper degradation is directly proportional to the water content. For example, decreasing the water content of the paper from 1.0% to 0.5% doubles the life of that paper. Thermally-upgraded paper insulation is less sensitive to the effects of water than Kraft paper.

Effects of Oxygen:

Paper aging is influenced by the presence of oxygen although not to the same degree as oil. Thermally-upgraded paper is even less sensitive to the effects of oxygen than Kraft paper. It has been suggested that the effects of high oxygen compared to low oxygen environments on the aging of Kraft paper is of the order of 2.5 to 1, which seems reasonable (based on our own experience in examining paper samples from service-aged transformers).

The expected life of dry (≤0.5% water) regular Kraft paper in an high oxygen environment (such as very old free breathing designs) is about 4 years performing operating at a temperature of 100°C (the expected hotspot temperature of a transformer at nameplate rating of 55°C rise). In contrast, the expected life of dry, thermally-upgraded Kraft (TU) paper in a low oxygen environment (sealed conservator or nitrogen blanketed) performing at a temperature of 110°C (the expected hotspot temperature of a transformer at nameplate rating of 65°C rise) is about 18 years [Griffin, Paul J., "Measurement of Cellulose Insulation Degradation: A Study of Service-Aged Transformers," Minutes of the Fifty-Ninth Annual International Conference of Doble Clients, 1992, Sec. 10, pp. 4.1-4.31].

It becomes apparent then, that the types of paper insulation and preservation system severely impact the expected life of the cellulosic insulation. Even so, if paper insulation is maintained in a dry state it will retain good electrical properties even as it becomes quite brittle.

Through the course of winding vibration and movement, however, particularly during through-faults, mechanically weakened paper can break, reducing insulating capability or allowing conductor movement and reduced clearances. It is then that dielectric failure is more likely to occur.

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GENERATION, DEGRADATION, AND ACCUMULATION OF FURANIC COMPOUNDS

The degradation of cellulose molecules results in the formation of gases, primarily carbon monoxide and carbon dioxide, and glucose, which in turn forms furanic compounds, and other byproducts.

Furanic compounds are not completely stable in transformers, and the final concentration is influenced by numerous factors. It has been our experience that there is a constant generation and degradation of furanic compounds so any net increase over time is considered to be accumulation.

Furanic compounds in transformers are generated from the degradation of cellulosic materials. RHowever, there can be residual furanic compounds can be present in some new oils, from excessive dry-outs, or from reused oils that should be considered in determining baseline values.

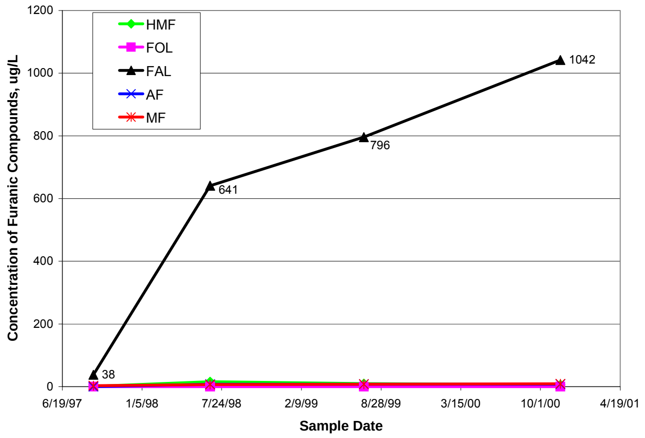
In the manufacture of new transformer oil several different refining processes can be used. One process involves solvent refining using 2-furfural. If it is not completely removed after the refining process then it will be present in the final product that is delivered. Residual concentrations as high as 380 ug/L have been found by testing performed at Doble.

Used oil from electrical apparatus may also contribute furanic compounds. Many utilities use oil storage farms in which oil from in-service apparatus is stored for reuse. This oil will often contain furanic compounds. If this oil is not processed prior to re-use it will contaminate the next apparatus that it used in. Reclamation of the oil is a very effective process of removing the furanic compounds.

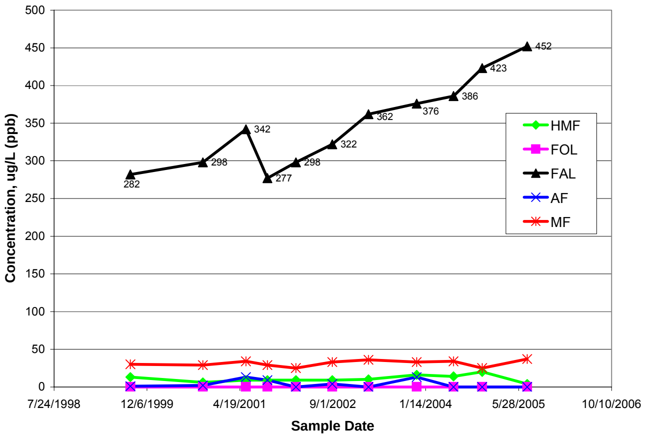
The treatment of the transformer and the oil at the transformer-manufacturing site might also contribute furanic compounds. Inadvertent overheating of the cellulose during dryout and/or heat run testing might degrade the insulation causing the production of furanic compounds. Even if the oil is removed prior to shipment and replaced with new oil upon receipt, furanic compounds in the cellulose will partition from the paper to the oil.

Observed General Patterns

Figures 1-5 depict three general patterns that are often seen in transformers that have not undergone any internal maintenance activities that would alter the amount of furanic compounds present. These examples are taken from free breathing conservator transformer with Kraft paper insulation and sealed transformers with thermally upgraded (TU) insulation. Figures 1 and 2 represent transformers in which the generation is greater than the degradation of furanic compounds, thus a net accumulation occurred suggesting active on-cellulose degradation.

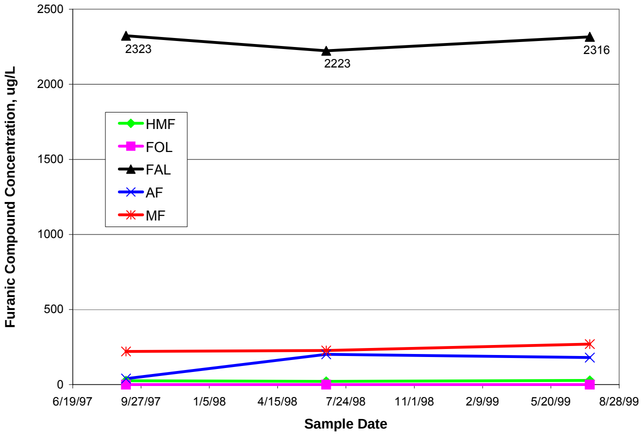


FURANIC COMPOUNDS INCREASE IN
OPEN CONSERVATOR
FIGURE 1

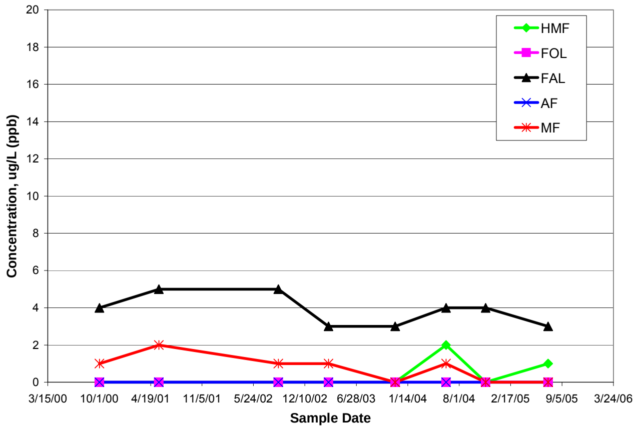


FURANIC COMPOUNDS INCREASE IN
SEALED CONSERVATOR
FIGURE 2

Figures 3 and 4 are graphs that indicate that the concentration of furanic compounds is relatively stable indicating generation and degradation is nearly equal and the generation rate is low.

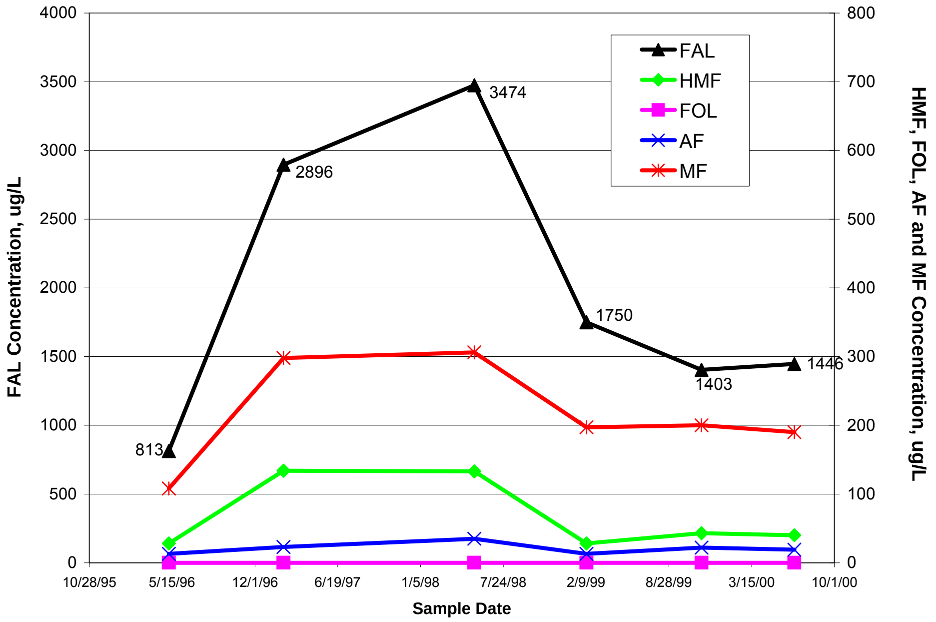


STABLE CONCENTRATION OF FURANIC
COMPOUNDS IN OPEN CONSERVATOR
FIGURE 3



STABLE CONCENTRATION OF FURANIC
COMPOUNDS IN SEALED CONSERVATOR
FIGURE 4

Figure 5 exhibits changes in furanic compounds resulting from a very interesting history for this transformer. In the beginning there is a rapid increase of furanic compounds, definitely suggesting there is an active overheating condition causing accelerated degradation of the cellulose insulation. Once the 2-furfural concentration reaches a maximum concentration of 3474 ug/L it starts to decline over time indicating that the overheating condition has somehow been repaired or mitigated and the degradation of the furanic compounds is quicker than generation, with the net effect of declining concentrations. Because this is a free breathing conservator transformer, the reduction in furanic compounds is most likely accelerated by the presence of oxygen. It is interesting that this type of rapid decrease is more typical in free breathing conservator transformers then in sealed conservator transformers.



FURANIC COMPOUNDS CHANGE OVER TIME
FIGURE 5

The amount of degradation of cellulose is based on the highest concentration of 2-furfural determined over time not necessarily the most recent sample (Figure 1). A reduction in 2-furfural is not an indication of a self-healing process. The reduction of furanic compounds is due to their degradation. Using the information from Figure 5 and the conversion to DP by the Chendong equation, the information in Table 1 is provided.

TABLE 1

CONVERSION OF FURANIC COMPOUNDS TO DP

2-Furfural Content, ug/L	Estimated DP
813	454
2896	297
3473	274
1750	359
1403	387
1446	383

Paper insulation with DP values below 200 are considered near or at the end of the reliable life, as it becomes mechanically compromised. Midlife is approximately a DP of 400 and new paper typically has a DP of about 1000 to 1300. In the example presented in Table 1, there is a large difference between the values. In this case, the maximum concentration of 3473 ug/L of 2-furfural with an estimated DP of 274 should be used for the reasons stated previously.

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FACTORS THAT INFLUENCE THE CONCENTRATION AND STABILITY OF FURANIC COMPOUNDS

The concentration of furanic compounds present in the oil can be significantly impacted by several factors. The following issues have been identified as affecting the generation, stability, and accumulation. In the paper used as a basis for this article the issues listed below were explored in detail.

- *Effects of oil degassing by partial vacuum*
- *Effects of mechanical filtration (reconditioning)*
- *Effects of oil reclamation*
- *Effects of oil change-out*
- *Stability of furanic compounds in oil*
- *Kraft, thermally-upgraded (TU) Kraft, varnish and epoxy coatings and Nomex® insulation systems*
- *The Generation of 2-Furfural in Kraft, TU and mixed insulation including the effects of dicyandiamide (DICY) and "Cross Pollination"*
- *Partition coefficients*
- *Effects of electrical discharge and high temperatures*
- *The role of the transformer preservation system*

CONCLUSIONS

The analysis of furanic compounds in oil can provide valuable information for assessing the condition of the cellulose insulation. It is also apparent that the more specific information known about a transformer and its family, the better the diagnosis, as populations can be significantly different.

Furanic compounds are reduced in concentration by such maintenance activities such as oil degassing, change-out, reclaiming and reconditioning. Examination of residual amounts of furanic compounds after maintenance activities has been shown.

Partial discharge and arcing conditions can locally damage the cellulose insulation and yet not produce significant quantities of furanic compounds. They appear to be degraded at the temperatures in which those incipient-fault conditions take place.

Chemicals in the insulation used for thermal upgrading such as dicyandiamide significantly reduce the concentration of furanic compounds in the oil. Data from a furanic compound analysis should be treated carefully. As shown described in the paper upon which this article is based, Doble has developed a scheme for determining the difference between normal and accelerated aging based on the insulation type and preservation system present. The categories are as follows:

- Kraft paper insulation and free breathing conservator
- Kraft paper insulation and sealed system
- TU-Kraft paper (chemical addition) and free breathing conservator
- TU-Kraft paper (chemical addition) and sealed system

It has been found that transformers in these categories produce different amounts of furanic compounds at varying rates and should not be grouped together as a single population. Using rates of accumulation aids in determining if a fairly new transformer may have an abnormal overheating condition much sooner than concentration limits alone. For example, if a new transformer (sealed, TU-Kraft insulation) within the first six months of operation produces a concentration of 35 ug/L, in most cases it would assumed to be operating normally, since it is less than 100 ug/L. However, the 2-furfural accumulation rate is 70 ug/L/year, which is excessive and indicative of accelerated heating of the cellulose insulation.

AUTHOR BIOGRAPHY

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Lance Lewand is the Laboratory Manager for the Doble Materials Laboratory and is also the Product Manager for the Doble ***DOMINO***®, a moisture-in-oil sensor. The Materials Laboratory is responsible for routine and investigative analyses of liquid and solid dielectrics for electric apparatus. Since joining Doble in 1992, Mr. Lewand has published numerous technical papers pertaining to testing and sampling of electrical insulating materials and laboratory diagnostics. Mr. Lewand was formerly Manager of Transformer Fluid Test Laboratory and PCB and Oil Field Services at MET Electrical Testing Company in Baltimore, MD for seven years. His years of field service experience in this capacity provide a unique perspective, coupling laboratory analysis and field service work. Mr. Lewand received his bachelor of science degree from St. Mary's College of Maryland. He is actively involved in professional organizations such as ASTM D-27 since 1989 and is a sub-committee chair. He is also the secretary of the Doble Committee on Insulating Materials.