Transformer Insulation Dry Out as a Result of Retrofilling with Natural Ester Fluid

Steve Moore, *Senior Member, IEEE*, Kevin Rapp, *Member, IEEE* and Ramona Baldyga

***Abstract*-- Transformer cellulose insulation generates moisture as it degrades, primarily dependent on temperature. As moisture levels increase in paper/liquid systems, dielectric performance decreases. Moisture in cellulose insulation combined with higher temperatures accelerates the cellulose aging process. Multiple accelerated life tests in the lab demonstrated that the aging rate of cellulose can be significantly slowed when impregnated with natural ester fluid compared to mineral oil. The reduction and suppression of moisture buildup in cellulose is the primary reason for the reduced aging rate. This paper reviews chemical mechanisms involved based on laboratory studies and field data from fourteen power transformers retrofilled with natural ester fluid. The data provides support that insulation dry out can result from moisture migration and hydrolysis after retrofilling transformers with natural ester fluid. The concepts of moisture migration, hydrolysis and dry out are beneficial for new transformers as well and should work to maintain like-new dry insulation conditions.**

***Index Terms*—accelerated aging, chemical processes, dielectric liquids, hydrolysis, insulation, mineral oil, moisture, natural ester, power transformers, retrofilling, vegetable oils**

I. Introduction

THe fact that moisture is generated in transformers as the cellulose insulation ages at elevated temperature is well known. As the moisture content of the insulation system increases, dielectric strength drops. Moisture in the insulation system, combined with higher temperatures, will accelerate the cellulose insulation aging process. Multiple accelerated life tests in the laboratory have demonstrated that the aging rate of cellulose insulation can be significantly slowed when impregnated with natural ester (NE) fluid compared to mineral oil (MO).

It is common knowledge in our industry that drier cellulose insulation has a longer life. There are two primary reasons for moisture reduction of the cellulose in NE fluid:

1. Moisture Migration - Moisture will establish equilibrium between the cellulose insulation and the fluid. Retrofilling an aged MO filled transformer with NE fluid will typically result in moisture migrating from the cellulose into the NE fluid until equilibrium is established. NE fluid holds significantly more moisture in solution than MO at the same percentage of saturation while maintaining equivalent dielectric strength.
2. Hydrolysis - Moisture dissolved in the NE fluid will react with the fluid via the hydrolysis reaction to form long chain fatty acids. This takes the moisture out of the equilibrium process between the insulation and the NE fluid resulting in lower percent saturation for both.

Related but separate studies done previously described another chemical reaction between the long-chain fatty acids generated by hydrolysis of the NE fluid and the hydroxyl groups attached to the cellulose molecule called transesterification [1]-[4]. This reaction can enhance the stability of paper and reduce the formation of new moisture due to the degradation of cellulose but is not discussed in further detail in this paper. Continued research into transesterification could provide more insight into possible cellulose protection provided when NE fluid is used in lieu of MO.

Cellulose insulation aged in MO at elevated operating temperature produces and retains moisture due to the hydrophobic character of MO. NE fluid is hydrophilic compared to MO, so it attracts moisture. The higher the moisture content of the cellulose, the more the cellulose ages at an accelerated rate. Therefore, it is beneficial to reduce the moisture in the cellulose and maintain dryness.

This paper reviews field data from power transformers service aged in MO then retrofilled with Envirotemp™ FR3™ Fluid, a natural ester fluid manufactured by Cooper Power Systems. The operating history of fourteen units along with FR3 fluid testing provides supporting data that hydrolysis and cellulose insulation dry out can result from moisture migration after NE retrofilling of transformers. The concepts of hydrolysis and dry out are beneficial for new transformers as well and should work to maintain like-new dry insulation conditions.

II. Laboratory Investigations

The combination of the hydrolysis reaction and moisture equilibrium are the primary reasons for the reduction of moisture content in both the dielectric fluid and insulating cellulose.

A. Moisture Migration

NE fluid holds significantly more moisture in solution than MO at all temperatures as shown in Fig. 1. In an operating transformer containing fluid, the majority of moisture is held in the cellulose, not in the dielectric fluid. Because NE fluid can hold significantly more moisture as a percent of saturation compared to MO, more moisture can migrate from the cellulose and dissolve in the NE fluid. Thus, when using a new NE fluid retrofill of an older transformer as an example, the new NE fluid increases in water content while the cellulose insulation decreases. This same concept would hold true for a new MO retrofill of an older transformer, but not to the same extent. This moisture migration mechanism, by itself, is not enough to remove sufficient moisture to dramatically slow the aging rate of cellulose.

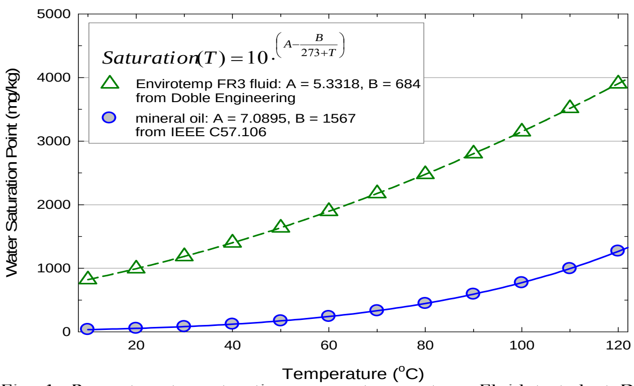

Fig. 1. Percent water saturation versus temperature, Fluid tested at Doble Engineering [5].

NE fluid maintains acceptable dielectric strength even though the fluid absorbs a greater amount of moisture compared to MO. The dielectric strength of the NE fluid as a percent of relative saturation is about the same or slightly higher than MO. See Fig. 2 and 3.

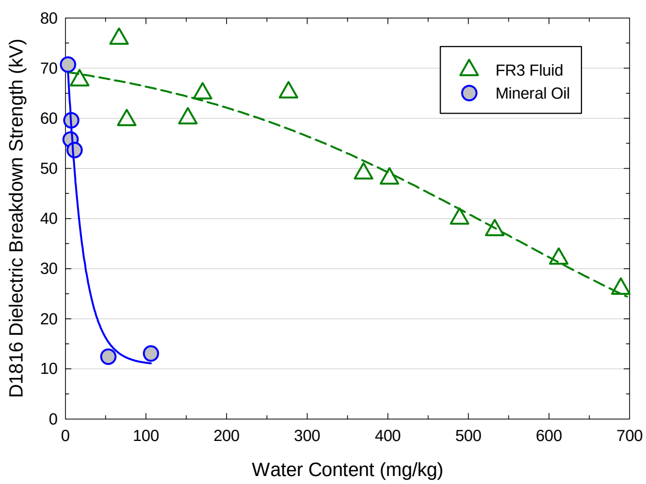

Fig. 2. Dielectric strength (2 mm gap) of new fluid vs water content [6].

B. Hydrolysis

Hydrolysis is a chemical reaction with water that further explains the significant moisture reduction observed in laboratory studies of cellulose insulation in NE fluid [7]-[9]. The dissolved moisture in the NE fluid reacts with the fluid to form new compounds called long chain fatty acids. This reaction occurs faster as the fluid temperature increases. The formation of these compounds consumes moisture from the dielectric fluid, making it unavailable to react with or migrate back into the cellulose. The fluid becomes drier, allowing additional moisture absorption from the cellulose and the percent moisture content of the cellulose to decrease.

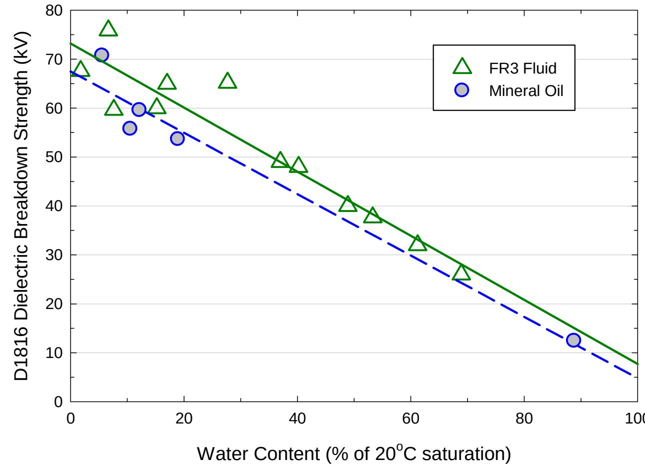

Fig. 3. Dielectric strength (2 mm gap) of new fluid versus % water [6].

Long-chain fatty acids that result from hydrolysis and are dissolved in the NE fluid will increase the acid number. The long-chain fatty acids are less aggressive organic acids than those formed from MO. Increased acid number in MO can cause sludge formation which could interfere with the rate of heat transfer, leading to higher winding insulation temperatures, cellulose aging and thermal failures. Lab tests conducted in a sealed container at 170°C for 2000 hours show virtually no signs of sludge formation from NE fluid, but show heavy sludging in MO at these same conditions per Fig. 4 [10].

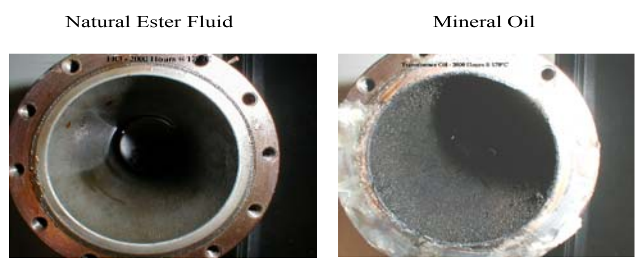

Fig. 4. Interior of aging tubes after 2000 hours at 170°C [10].

Acceptability of a higher acid number requires a paradigm shift. In MO, high acid number is undesirable and an indication that sludge may be depositing; in NE fluid, higher acid number is inconsequential and most often indicates that the cellulose and fluid are getting drier due to hydrolysis. Changes in moisture content and acid number of transformer cellulose and oil systems rely on the operating conditions placed on the transformer. For the concept of transformer dry out discussed in this paper, it is assumed and important that the transformer has operated in a sealed condition.

As moisture level in the NE fluid drops, it changes the equilibrium balance which allows the fluid to draw more moisture out of the cellulose. We expect that the hydrolysis process will continue until there is little moisture left to react, resulting in a significantly drier transformer.

C. Moisture Equilibrium

A study was conducted to investigate the equilibrium shift of moisture between NE fluid and cellulose insulation that may result, for example, in a retrofilled transformer [11]. To simulate a pre-retrofill condition, all cellulose insulation samples for the study were initially aged in MO at 170°C for 400 hours. These aging conditions reduced the cellulose insulation life by about 50%. At this stage, the moisture content of the cellulose samples was about 1% by weight. Half of the cellulose samples were removed from the MO and conditioned in a humidity chamber to a moisture content of 3% by weight (considered high moisture for insulating cellulose). The two groups of moisturized cellulose were divided between further aging in service-aged MO, in new retrofilled MO and in new retrofilled FR3 fluid. These groups were each then divided into three groups to be aged at room temperature, 85°C and 110°C for 2200 hours in sealed containers. Samples of paper and fluid were removed from the containers at selected aging times and tested for moisture content. The fluids were also tested for acid number. At a transformer operating temperature of 85°C for example, the moisture in the cellulose after retrofilling with NE fluid was reduced to nearly 0.5% by weight as shown in Fig. 5.

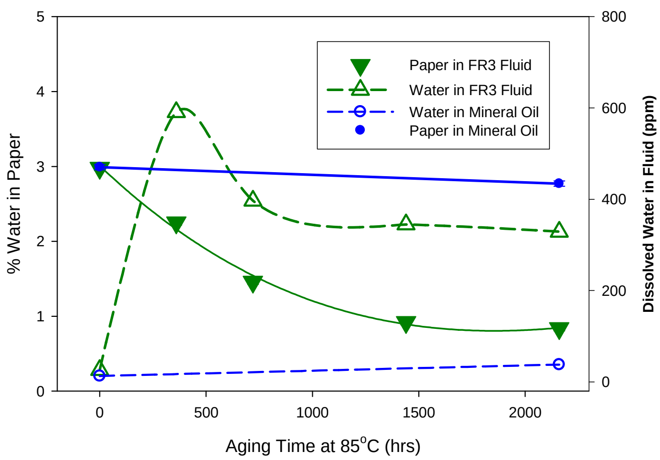

Fig. 5. Paper at 3 % moisture aged at 85 °C for 2200 hours in NE and MO.

As expected, due to moisture migration, the moisture content in the NE fluid initially increased as it absorbed moisture from the cellulose until equilibrium was established. As aging continued, the moisture content in the NE fluid decreased due to hydrolysis, which increased the acid number of the fluid, per Fig. 6 [11]. In all cases, the moisture content of the cellulose in the NE fluid dropped significantly whereas the moisture content of the cellulose in MO dropped only slightly, if at all, which agrees with other researchers [12].

Fig. 6 shows decreasing moisture in the cellulose and in the NE fluid, while the acid number of the NE fluid steadily increased due to formation of long-chain fatty acids. This supports the conclusion that hydrolysis occurred. Some full scale accelerated aging studies with transformer components found very low levels of copper and iron dissolved in the NE fluid, indicating that the acids formed are indeed milder than the acids formed in MO [7]-[9]. Short-chain acids formed in aged MO are generally more aggressive and at elevated levels will tend to accelerate reactions with transformer materials [13].

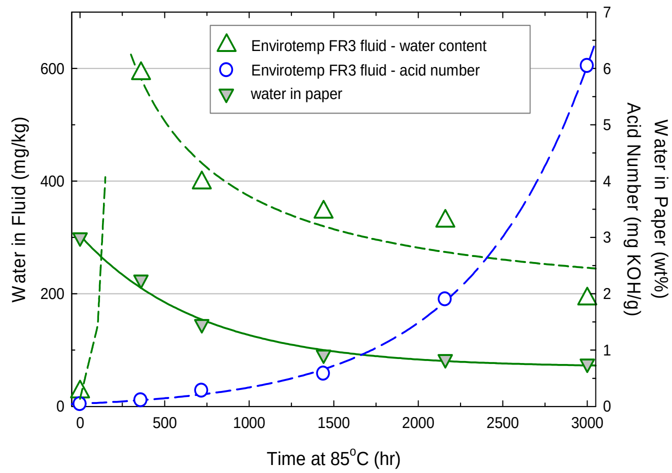

Fig. 6. Changes in moisture in paper and fluid, and acid no. vs time at 85°C

III. Field Data Analysis

Alliant Energy retrofilled fourteen MO-filled power transformers with NE Fluid. The average age of the transformers was 40 years when retrofilled between October 2001 and June 2007. Field samples and operational data included transformer and fluid temperatures, fluid moisture content and acid number. The field data included testing of MO samples collected prior to the retrofilling. The field data supports the hypothesis that, during transformer operation, moisture migrates from the cellulose insulation to the NE fluid. The speed and amount of moisture migration will depend on the operating conditions of the transformer before and after retrofilling with NE fluid.

As previously mentioned, the mechanism of hydrolysis will convert the moisture and some of the NE fluid into long chain fatty acids, resulting in an increase in the acid number of the fluid. Fig. 7 shows the change in the acid number of nine of the fourteen transformers retrofilled with NE fluid. There were five units

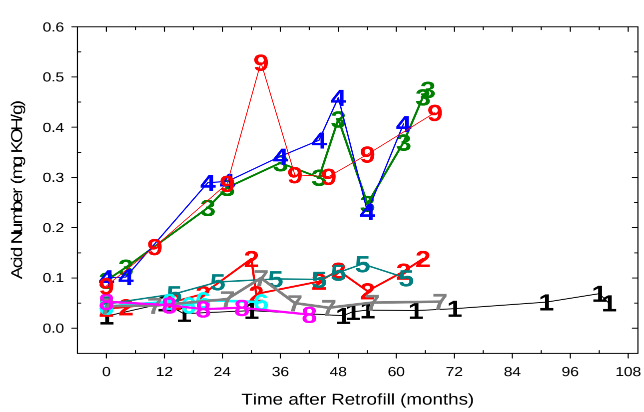

Fig. 7. Change in acid number of NE fluid in 9 of 14 field transformers

TABLE I
Transformer field data summary before and after NE fluid retrofilling

Unit No.	Type	*A* Age as MO (yr)	Retrofill Date	*B* Time since NE Retrofill (mo)	Oil Volume (gal)	*C* Ave Top Oil Temp (°C)	*D* MO Water Content (% saturation)	*E* Acid No. increase (%)	*DOF* Dry-Out Factor
9	Aux	39	May 2004	68	1,435	47	44	411	609
3	Aux	37	spring 2004	67	2,130	51	43	400	598
4	Excitation	37	spring 2004	62	5,680	29	35	307	470
2	GSU	37	spring 2004	66	10,200	55	31	254	443
1	GSU	44	Oct 2001	104	7,720	26	23	108	305
5	Aux (reserve)	37	spring 2004	62	2,160	23	23	108	253
10	Emergency	41	Apr 2006	42	2,160	38	35	40	196
7	GSU	10	2004	69	7,930	52	23	20	174
6	Aux	28	Jun 2007	32	3,765	51	21	21	153
12	GSU (peaking)	51	Dec 2006	14	13,767	20	21	8	114
11	Aux (peaking)	52	Nov 2006	14	1,600	20	26	0	112
14	Aux (peaking)	51	Dec 2006	14	1,600	22	26	-5	108
8	Aux	49	spring 2006	42	5,400	33	29	-49	104
13	GSU (peaking)	52	Dec 2006	11	13,767	14	21	-13	8

that exhibited little to no change in acid number and were not included in Fig. 7. These units have operated for shorter time periods and at reduced temperature. The transformer ID number was used to plot each of the individual acid values measured during the monitored time.

Three of the field units displayed in Fig. 7 contain NE fluid with significantly higher acid values. The acid levels in units 3, 4 and 9 indicate the extent of the hydrolysis reaction that took place since the transformers were retrofilled with NE fluid. Analysis and comparison of the field data provided a clearer understanding of the dynamics that promote transformer insulation dry out as a result of interaction with NE fluid. We begin the analysis by focusing on the field data summarized in Table 1.

The field data contains five variables that were used to assess the relative potential for change in moisture condition of the fluid and cellulose insulation in field transformers retrofilled with NE fluid. With units of the variables ignored, the values of the five variables were placed in equation (1) to derive a "Dry-Out Factor" (DOF) in which higher values equate to more hydrolysis. There is close correlation between the quantity of hydrolysis-generated fatty acids, shown as variable *E*, and the *DOF*. The other variables *A*-*D* provide a broader understanding of operating parameters that cause changes in fluid and cellulose insulation moisture. The data in Table 1 were sorted from largest to smallest DOF. Drier cellulose insulation has improved dielectric characteristics and longer life, concepts that are generally accepted.

$$DOF = A + B + C + D + E \quad (1)$$

Where:

A = age of the transformer as a MO unit.
B = time after retrofilling with NE fluid.
C = average top oil temperature during unit life – both MO and NE.
D = average percent moisture saturation in the MO before retrofilling.
E = percent increase in acid number of the NE fluid.

Changes in NE fluid moisture contents and acid number from two field transformers were plotted in Fig. 8. Unit 9 had the largest increase in acid number combined with the highest DOF values. Unit 1 was retrofilled with NE fluid for the longest time, but showed only a modest increase in acid number and a 50 % lower DOF value when compared to unit 9. Comparison of the two units using the change in fluid moisture with other data in Table 1 explains the dynamics of the dry out process and how it progresses.

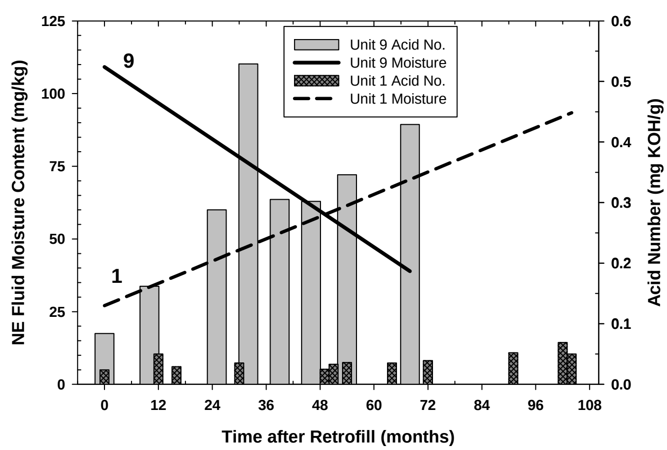

Fig. 8. NE moisture content and acid number after retrofilling units 1 & 9

Fig. 8 shows the significant reduction in fluid moisture from unit 9 while the acid number steadily increases, which supports the mechanism of hydrolysis. Two factors are important to explain why unit 9 has the highest DOF. The most important is the level of moisture that was held in the MO and associated solid insulation prior to retrofilling.

There is a direct correlation between high moisture conditions before retrofilling and high DOF of the NE fluid afterwards. The percent moisture saturation in the MO is used as a relative gauge of the amount absorbed in the cellulose insulation. The other important factor is the average temperature of the transformer. Higher temperatures increase the rate of the hydrolysis reaction, which depletes the moisture and produces acids. Unit 1 is plotted in Fig. 8 in contrast with unit 9.

The moisture content of the NE fluid in unit 1 increased significantly with time after retrofill instead of decreasing while, at the same time, the acid number increased only slightly. Why? The average moisture dissolved in the mineral oil, the temperature of transformer operation, and the time in service before and after retrofill provides the answer. These conditions for unit 1 were not favorable for the hydrolysis mechanism. The increase in moisture content in this case can be attributed to the length of time that the NE fluid had to absorb moisture from the solid insulation, which shows that moisture migration has occurred. The acid number did not increase because the temperature was not high enough to significantly drive hydrolysis

Of the top ten units that were retrofilled for ≥ 32 months with NE fluid, six showed decreasing moisture in the NE, three showed increasing and one was flat. This is understandable because the fluid is the conduit that removes moisture from the cellulose at a certain rate and reacts with the moisture via hydrolysis to deplete it at a different rate, both dictated by the residual moisture in the cellulose at the time of retrofill and the operating temperature of the unit thereafter. Even though temperature drives the hydrolysis reaction rate, the moisture must be present initially.

The change in fluid moisture in unit 9 correlates with the highest DOF. The data indicates the importance of the initial moisture condition of the transformer insulation, shown as [D] in Table 1, combined with top oil temperature. The conditions of unit 9 favor dry out via hydrolysis and formation of long-chain fatty acids.

Fluid moisture and acid number results from field units 2 and 3 are plotted in Fig. 9. Comparison of the units again shows the primary importance of elevated moisture levels in the MO prior to retrofilling combined with top oil temperature to generate fatty acids and high dry out factors. Higher moisture levels in unit 3 produce up to four-times the acid number compared to unit 2. The relatively high top oil temperature drove the hydrolysis reaction, which reduced the moisture level in the cellulose insulation.

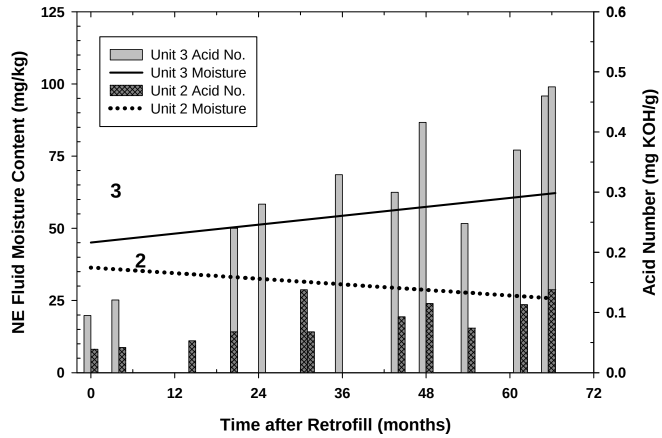

Fig. 9. NE moisture content and acid number after retrofilling units 2 & 3

IV. Conclusions

The moisture content in cellulose insulation is proportional to its aging rate – an increase in the moisture content results in an increase in cellulose aging, resulting in an additional increase in moisture content. Retrofilling a mineral oil-filled transformer with natural ester fluid will reduce the cellulose moisture content and therefore its aging rate. Since the natural ester fluid can hold more moisture in solution than mineral oil, moisture will migrate from the cellulose into the natural ester, reducing the cellulose moisture content. The dissolved moisture hydrolyzes with the natural ester fluid, consuming moisture in the fluid, producing free fatty acids and an increase in the acid number. As hydrolysis consumes moisture, the equilibrium shift draws more moisture out of the cellulose into the fluid. Thus, moisture is eliminated during the hydrolysis reaction and will not return into solution in the fluid or cellulose.

Field data supports the theory of moisture migration from the cellulose into the NE fluid, as well as the chemical process of hydrolysis converting water and the NE fluid into a new compound—long chain, fatty acids. The long chain, fatty acids stay in solution and do not impact performance. Certain variables play a key role in the extent of insulation dry out. These include water saturation of the cellulose at the time of NE retrofill along with operating temperature of the transformer after retrofill. There has to be sufficient water available to support hydrolysis. Higher temperatures due to ambient and load conditions accelerate the hydrolysis process. Sufficient time is required to allow for moisture migration and the hydrolysis reaction to occur. The overall concept, identified as the “Dry-Out Factor” (DOF), can be correlated with the following transformer conditions (most important listed first):

1. Moisture content of the cellulose insulation
2. Average top oil temperature of the transformer
3. Increase in acid number of the natural ester fluid
4. Age as a natural ester filled transformer

5. Age as a mineral oil transformer prior to retrofilling with natural ester fluid

Higher DOF values suggest that more moisture has been removed from the insulation system.

The data leads the authors to conclude that retrofilling a service aged mineral oil transformer with natural ester fluid will remove water from the insulation system. This conclusion assumes there is sufficient water in the cellulose to support hydrolysis and that the operating temperature is in the medium to upper range of normal transformer operating temperatures. Dry insulation is a benefit to the transformer owner because it slows the aging rate of cellulose and extends the life of the asset. Natural ester fluid in a new transformer is expected to maintain cellulose insulation dry.

V. References

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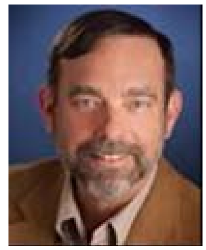
VI. Biographies



Steve Moore graduated from the Milwaukee School of Engineering in 1974 with a B. S Engineering Technology-Electrical degree. He has also attended month long management seminars at the Schools of Business of the University of Wisconsin, Madison and the University of Southern California. His employment experience has all been with Waukesha Electric Systems and all of its previous company names. He spent 26 years in new transformers in various marketing capacities including Sr. Application Engineer, Product Manager and Market Manager. He spent 2 years working as Business Development Manager for WES's Power Systems Development subsidiary developing EPC substation projects and 3 years as Market Development Manager for WES's Service business unit. Steve then moved back to the transformer group as the Product Manager for LTC and Natural Ester Fluids. In 2010 Steve was promoted to Director-Transformer Product Management. Steve has been an IEEE member for 40 years and was elected to the grade of Senior Member in 1990. Steve and other colleagues were the recipients of The Institute of Management Sciences Franz Edelman Management Science Achievement Award for 1989 for Waukesha Electric System's use of innovative management science. Steve is also listed in the Acknowledgements of NBS Technical Note 1204 titled Calibration of Test Systems for Measuring Power Losses of Transformers, for having made significant contributions to this effort.

Kevin J. Rapp is a Senior Project Engineer for Cooper Power Systems. He received a B.S. in Chemistry from the University of Wisconsin-Parkside in 2003. Prior to joining the Cooper Power Systems Dielectric Fluids Marketing group in 2004, Kevin spent 27 years as a technician and chemist with the Thomas A. Edison Technical Center. He has been involved with dielectric materials development for electrical power equipment and is one of the Inventors of the natural ester, Envirotemp® FR3® Fluid, and it's use in electrical equipment. Kevin holds numerous U.S. and international patents and has written many technical papers. He was recently awarded the IEC "1906 Award" for acheivement as an International expert in natural ester fluids and is a member of the Technical Advisory Group to the United States National Committee for IEC TC10. Kevin is chairman of ASTM D27.15 Subcommittee and leads an ASTM task group on oxidation stability test methods for natural ester fluids. He is a member of IEEE, ACS, AOCS, ASTM, and CIGRE.

Ramona Baldyga, P.E., graduated from the University of Kentucky in 1975 with a B.S. in Mechanical Engineering. She has worked for Alliant Energy and its predecessor companies in various capacities since 1984. In her current position of Senior Engineer, she is responsible for the substation predictive maintenance program, including dissolved gas in oil analysis, infrared, vibration and acoustic monitoring, and has been actively involved in substation equipment condition assessments for the past 15 years. She received her Iowa Professional Engineering license in Mechanical Engineering in 1990.