Dissolved Oxygen and Moisture Removal System for Freely Breathing Transformers

J. Sabau[1], I. Fofana[2], Y. Hadjadj[2] and M. Brahami[3]

[1]InsOil Canada Ltd, Canada

[2]Canada Research Chair on Insulating Liquids and Mixed Dielectrics for Electrotechnology (ISOLIME), University of Quebec at Chicoutimi, Qc, Canada

[3]Laboratoire ICEPS, Département d'électrotechnique, Faculté de l'ingénieur, Université Djillali Liabès de Sidi Bel Abbès, 22000 Algérie

***Abstract* - In this contribution, the outcome of an industrial experiment designed to demonstrate a new nitrogen blanketing system is presented. The technical solution involved purging of the oil surface in the conservator by a constant flow of pure nitrogen. Analysis performed over an 8 years period; clearly indicate that this innovative, environmentally friendly, and economically affordable technique can arrest/reduce the oxidation decay process of oil-paper insulation in free breathing power transformers.**

I. Introduction

Power transformers are considered capital investments in the infrastructure of every country in the world. They are the “heart” of any electric power distribution and transmission systems and it is essential that they function properly. The recent blackouts (e.g. in the United States, Brazil and Europe) underscored the importance of reliable electrical energy systems. Extreme reliability is demanded of electric power distribution as when failures occur they inevitably lead to high repair costs, long downtime and possible personnel safety risks. In addition environmental aspects such as consequential damages, fire and pollution are of high risk.

In this important equipment, the most widely used insulation systems for nearly a century [1, 2] are liquid insulation (petroleum-based oil, the so-called transformer oil) combined with solid insulation (kraft paper, pressboard, wood i.e. cellulose products). When the solid paper is adequately impregnated with oil, it offers the user a material with insulating and mechanical properties of remarkable suppleness. The ready supply and cost benefit of cellulose and mineral oil has, therefore, made these the materials of choice for nearly a century [2].

Under the combined impact of electrical stress and thermal stress the oil starts evolving gases [3]. The gassing of oil raises the population of chemically highly reactive free radicals. Therefore, the random chemical reactions between the broken hydrocarbons and the oxygen molecules are inevitable [1, 4]. Beside gases that dissolve in the oil, the gassing generates colloidal sludge as well. The accumulation of these insoluble particles leads to the formation of incipient electrical failures. Thus, the gassing of oil becomes a self-sustained process [4, 5]. Rubber bladders or nitrogen cautions that seal the transformers are other solutions to stop the oxidation decay process of oil. As the spectral ASTM test method D6802 demonstrates, none can stop the absorption of oxygen from the atmosphere [6]. Even though the content of dissolved oxygen is reduced from 20000 below 5000 ppm, the oxidation process continues [7]. The ASTM stability test D6180 shows that under the impact of electrical stress certain oxidation products are decomposed. Concomitantly, due to random secondary chemical reactions the turbidity measured by ASTM test method D6181 [8] goes up. Solely the quantitative removal of dissolved oxygen is able to keep the liquid insulation in pristine condition for the entire lifetime of power transformers.

II. Insulation Ageing

Even though power transformer are properly designed and tested prior to installation there can be no guarantee that a fault within the insulation system will not occur in the future. Oil and other materials in a transformer degrade with time in service. The solid insulation cannot be restored unless the transformer is completely overhauled, unlike oil, which can be replaced when needed. The life of the transformer is actually the life of the internal insulation system.

The ageing or deterioration of insulating oil is normally associated with oxidation under the very harsh environment. Electrical stress together with heat and moisture in the presence of oxygen from air oxidises the oil producing free radicals, acids and sludge [1, 9-11]. These by-products are deleterious to the transformer and catalyze further oxidation of the oil. Aggressive decay products being adsorbed by the solid insulation attack on the cellulose fibers and also kill new oil after refilling. Sludge produced may stick onto the large surface of transformer boards stopping heat being dissipated. The sludge acts as barrier to the flow of heat from the oil to the cooling unit and from the core to the coils to the cool oil. Sometimes the sludge may even block the cooling ducts in which the oil flows. As a result, the transformer insulation and windings becomes too hot and would eventually be damaged thermally. Absorption of oil aging products by cellulose also masks real condition of the oil when traditional characteristics as acidity, dielectric dissipation factor are tested.

The cracking process of cellulose (depolymerisation by a succession of chemical reactions) causes chain scissions, the release of gases and water into the surrounding oil and some large molecules such as furfurals [12]. A simple schematic representation of the main processes and components released is shown in Figure 1. Moisture, which is considered as the enemy number one of the solid insulation, acts as catalyst and by-product at the same time [12, 13].

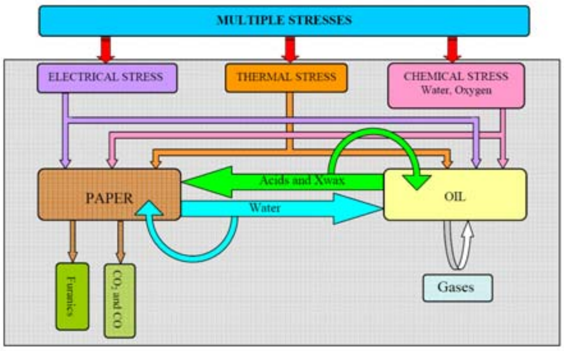

Figure 1. Interaction between different aging products and power transformer insulation system.

If the insulation systems were operated in perfect conditions, the need for testing would be needless. However, this insulation system deteriorates in time due to service conditions. In properly designed transformers, according to IEC 76-2 (thermal layout), the paper can last up to 55 years or more, provided there are no other thermal or dielectric defect present [12]. An appropriate maintenance strategy can allow a power transformer to safely function for 50 to 75 years. However, the maintenance of the insulation system largely determines the extent of a transformer's life. The Achilles' heels of paper are temperature and moisture. Cellulose can degrade rapidly at temperatures higher than 90°C [14]. The aging rate doubles roughly for each 8°C rise [14] while showing an approximately proportional aging rate to water content. For example, the life of cellulose pressboards at 110°C is calculated as ten years [15].

III. THEORETICAL BACKGROUND

The concept of quantitative removal of oxygen dissolved in the liquid insulation of windings is based upon the scientific premise that its peculiar chemical and physical properties are incompatible with the functions of this blend of hydrocarbons. The very special features of oxygen molecule that justify the above statement are the following.

- The oxygen molecule has two unpaired electrons with parallel spins. Since its ground state is a triplet, non-excited oxygen is paramagnetic. Due to this particularity it is attracted to the electro magnetic field of windings where its concentration is higher than in samples taken from the tank for DGA.
- Because of these two unpaired electrons the oxygen molecule is a highly reactive free radical. Consequently, the oxidation of free radicals generated by the gassing of oil is inevitable. These random chemical reactions have a negative effect on the interpretation of DGA.
- Free radicals that capture free electrons become charge carriers and raise the dissipation factor of oil. A growing population of such precursors, including paramagnetic oxygen molecules, pave the way for partial discharges
- The first excited states of oxygen are singlet states. These states are characterized by a very long lifetime. The transfer of this excitation energy to vulnerable hydrocarbon molecules increases the likelihood of gassing.
- When the oxygen molecule couples its free electrons with two large free radicals, large very unstable peroxides arise. This ignored side effect of gassing is the source of insoluble colloidal sludge that hinders the flow of heath from the active part to the radiators [11].
- The oxidation test does not properly simulate real life conditions because the free radicals generated by the gassing of oil are missing. The oxidation inhibitors can delay the oxidation process but cannot arrest the secondary chemical reactions between free radicals.

Currently, these fundamental chemical and physical properties of oxygen molecules are not taken in account. As a result, the existing maintenance procedures diminish ahead of time the service reliability of aging transformers. Just reliability centered maintenance techniques monitored by accurate laboratory tests can avoid the irreversible deterioration of paper insulation. The interpretation of DGA can be meaningful and cost effective only if the premature deterioration of paper insulation is carefully prevented.

IV. FREE BREATHING VS SEALED UNITS

Free breathing transformers are equipped with an oil reservoir to permit a variation in insulation oil volume. The volumetric change is due to the load and the atmospheric temperature variations. These temperature variations can cause up to a 9% change in volume. As the oil is in direct contact with the air, it absorbs moisture and oxygen which are both harmful to the oil itself and consequently to the solid insulation.

The main mechanism of water ingress inside transformers is the vicious flow of moist air. Air flow is caused by the volumetric variation of the liquid insulation. The increase of water content in transformers may result in free water formation and bubbling; it also increases electric conductivity and dissipation factor and worsens electric strength thus increasing the risk of breakdown. To hinder moisture inhalation from outside the transformer, a dehydrating breather containing silica-gel is introduced at the end of the air inlet pipe of the conservator.

The advantage of the air-breathing transformer is the absence of pressure variations. This system could theoretically allow gases, including decomposition gases and water as a product of cellulose ageing, to escape, while the most uncontroversial disadvantage is the near saturation of the oil with oxygen. It is now well established that oxidation is one of the dominant processes in the deterioration of insulating oil. According to Henry's law, the amount of gases dissolved in mineral oil is dependent upon the partial pressure of existing gases above

the surface. This is the reason why the oil in contact with air at atmospheric pressure dissolves 10% air by volume. To hinder the attack of oxygen molecules, oxidation inhibitors are added to these very complex blends of hydrocarbons [1]. As the ASTM D2440 [16] test shows, the chemical stability improves but the additive is slowly decomposed by the attack of oxygen. Since the anti-oxidant is a consumable material, the initial chemical stability of new insulating oil gradually decreases. Their amount has to be monitored and must be replenished if necessary.

Two mechanical solutions are available for hindering the contact of the oil with the outside atmosphere [17]. One method favoured in the United States is to seal the transformer using a nitrogen cushion. The other method is to use an elastic rubber or plastic bag to separate the surface of the oil from the gas space in the conservator. The diaphragm is flexible and floats on the oil surface in the conservator, in close contact with it. However, problems arising from the susceptibility of the membrane to chemical attack and physical wear, e.g., abrasion, have caused many transformer operators to turn to other solutions.

With both systems, contact of the oil with the atmosphere is impeded. Thus, deterioration of the oil through oxidation and moisture absorption is reduced.

V. INVESTIGATING THE HARMFUL IMPACT OF OXYGEN IN LABORATORY CONDITIONS

A. Experimental procedure

The effect of oxygen on the aging process of insulating systems in both sealed and free breathing transformers have been simulated under controlled laboratory conditions. Samples of paper specimens of about 81 x 81 mm² (dimensions were chosen to fit the test cell for solid insulations type 2914 manufactured by Tettex) were impregnated with dehydrated and degasified oil for 24 hours. The paper samples were used as received from the manufacturer without being dried. Aging was achieved by placing the impregnated papers specimens in a convection oven at 160°C and heating them for different periods of time. The prepared specimens were aged within sealed and unsealed vessels (Figure 2).

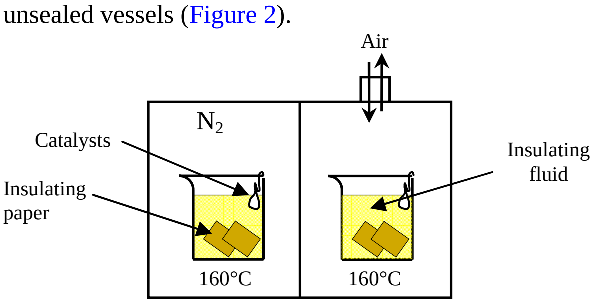

Figure 2. Insulation aging arrangement with/without air/oxygen inlet.

The paper specimens were placed in beakers containing different types of oil. Each vessel contains oil/paper samples. The procedure involves ageing the new materials within sealed/unsealed vessels. To simulate the effects of metallic components in the transformer, metallic catalysts (3 g/l of zinc, copper, aluminum, and iron) were introduced in a filter paper immersed in the oil. The beakers were placed in the oven at 160°C. Specimens were heated for 48, 72 and 96 hours. Electrical and physical tests were then performed on the aged samples. For the dielectric tests, the test cell for liquid insulation type 2903 by Tettex was used.

Two paraffinic petroleum based oils, referred as P1 and P2, were used in these investigations.

B. Chemical testing: DDP and Turbidity

Figure 3 shows the evolution of the DDP as a function of aging duration. The assessment of oils' turbidity as a function of aging duration, are summarized in Figure 4.

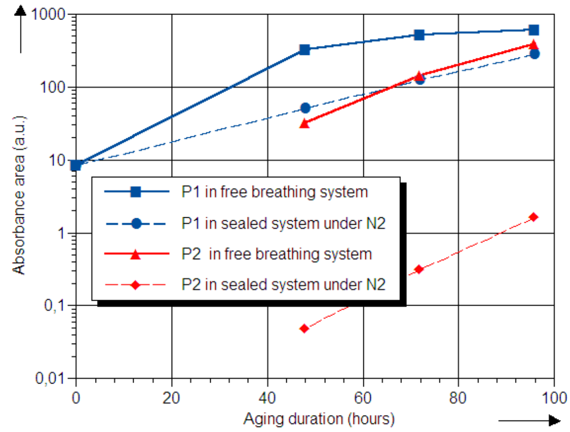

Figure 3: Effect of thermal aging on petroleum based oils' soluble decay products, with and without oxygen influence.

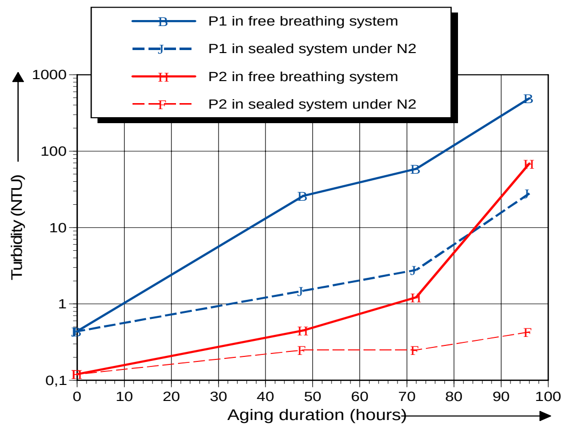

Figure 4. Effect of thermal aging on petroleum based oils' insoluble decay products, with and without oxygen influence.

Table I summarizes the ratio R between the measured physical quantity (turbidity or DDP) at a specific sampling time for samples undergoing accelerated aging with air inlet to the measured quantity for samples aged without oxygen

$$(R = \frac{Q_{\text{air inlet}}(\text{x hours})}{Q_{N_2\,\text{blanketed}}(\text{x hours})} .100).$$

The results emphasize the harmful impact of oxygen accelerated by heat. The DDP and turbidity generated under

nitrogen cushion are much lower than that of the open beaker with air inlet. The degradation rate reached values as high as 652%.

TABLE I. RATIOS OF DECAY PRODUCTS CAUSED BY THERMAL STRESS WITH AND WITHIOUT OXYGEN INFLUENCE

Testing	Aging duration (hours)	Ratio R (%)	
		P1	P2
DDP - D 6802 (area)	0	100	100
	48	6.47	652
	72	4.01	452.62
	96	2.07	237.32
Turbidity D 6181 (NTU)	0	1	1
	48	17.38	1.8
	72	20.89	4.88
	96	17.5	159.76

C. Electrical testing: Dielectric dissipation factor

From the frequency scan of dielectric dissipation factor (DDF), only the values at 50 Hz are reported in Figure 5. The DDF are lower for oil samples aged under nitrogen, which means improvement. The high values of natural esters' DDF compared to those of P2 and P1 can be attributed to polar contaminants.

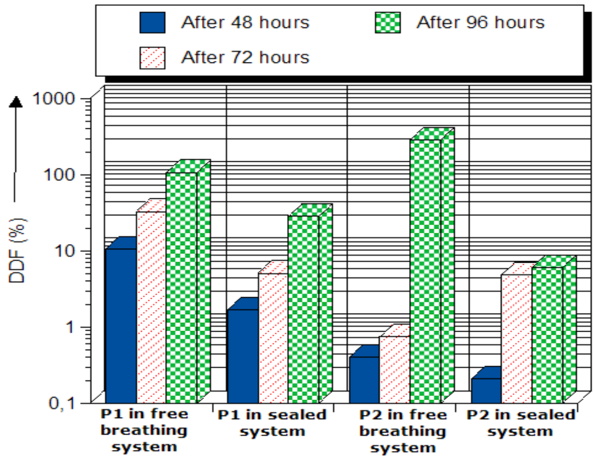

Figure 5. Effect of thermal aging on petroleum based oils' DDF, with and without oxygen influence.

Table II shows the DDF of oil-impregnated paper measured at line frequency (50 Hz).

TABLE II. DDF OF AGED OIL IMPREGNATED PAPER WITH AND WITHOUT AIR INLET (AFTER 96 HOURS).

	New sample	Aged with air (O_2) inlet	Aged under N_2
P1	2.052	2.302	0.684
P2	2.059	8.580	0.540

It can be seen that the dielectric properties of paper improve when partnered with oil sample aged without oxygen inlet. The improvement in the case of oil P2 is calculated to be 16 times when compared to the sample aged in the opened beaker. This should be traced to two important facts: the oxidation process is hindered / reduced due the absence of oxygen on one hand, and on the other hand the dry nitrogen above the beaker extracts moisture from the oil (and so to speak from the paper) while simultaneously excluding air (oxygen) from the system. Sealed transformers have a great advantage over air-breathing types as long as they remain air proof, but they have their own limitations and shortcomings. Theoretically, free-breathing units have an advantage over sealed units in that they allow some of the water produced by the cellulose aging process to escape through the conservator because the water concentration in the oil in the conservator will become greater than that of the air that has been sucked in through the dehydrating breather.

There is no doubt that by limiting oxygen access to the oil, one reduces the probability of premature deterioration of the insulation. However, none of the methods discussed takes into account the effect of high electric fields on the chemistry of oil. The dissolved gases generated by the decomposition of oil under electrical stress remain dissolved in the oil. Diffusion into the gas space of the expansion chamber, and subsequently into the surrounding atmosphere, does not occur.

VI. AN INNOVATIVE NITROGEN BLANKETING SYSTEM FOR FREELY BREATHING UNITS

A. Effect of the removed dissolved oxygen

Even under normal operating conditions, in addition to evolving gases, large molecules with an unpaired electron remain in the liquid phase. A first step in finding a proper technical solution for efficiently preventing the deterioration of oil is to point out the real causes of the decay process. Laboratory and field experiences have demonstrated worldwide that paramagnetic nature of oxygen can adversely affect the dielectric properties of solid insulation. According to Fabre and Pichon [18], reducing the oxygen concentration in the oil from 30,000 ppm to less than 300 ppm reduces the aging by a factor of 16. Thus, it is even more obvious that the quantitative removal of dissolved oxygen from the oil of power transformers is not a choice, but a must!

Instead of using anti-oxidants or sealing power transformers, a nitrogen blanketing system for freely breathing units was proposed and patented [19].

The novelty of this nitrogen blanketing system which is in place in Alberta, consists in the fact that the surface of oil in the expansion chamber is separated from contact with the outside atmosphere, while maintaining the free breathing character of the transformer. Thus, by purging the surface of oil with a continuous flow of high purity (99.5%) nitrogen (Figure 6), the dissolved oxygen in the oil is replaced by nitrogen, a chemically inert gas.

Eliminating the very cause of the threat to the chemical stability of the oil enhances operational safety while significantly reducing the cost of preventive maintenance. Nitrogen was chosen because it is chemically inert, environmentally friendly and relatively inexpensive. It lowers the dissolved gas content of oil by approximately 1.5% compared to air (10% by volume).

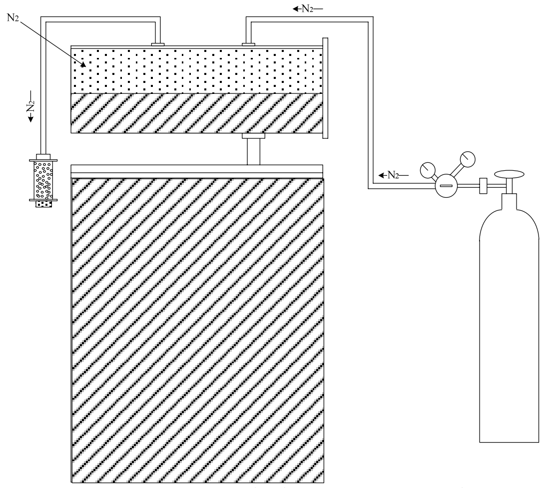

Figure 6. Nitrogen blanketing system for freely breathing transformers.

Two 5 MVA distribution transformers, were utilized for trials of the system. Both were loaded below 50% of their full capacity, so that the temperature of the oil (a brand insulating oil made from fully refined napthenic stocks) never exceeded 40°CFour oil samples were taken monthly from each unit for dissolved gas analysis. The resulting data, collected over a ten month period, showed clearly that the system removes dissolved oxygen from insulating oil, from 28,000 to approximately 5,000 ppm while maintaining the freely breathing character of the transformer. As the plots in Figure 7 illustrate, the dissolved oxygen content of oil in blanketed transformer #2 gradually decreased over the experimental period. As expected, the decrease of oxygen content was faster in the conservator, where the oil was in direct contact with the nitrogen blanket and slower in the tank.

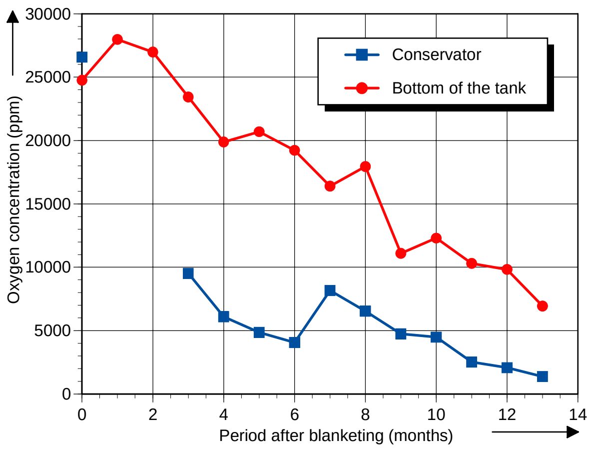

Figure 9. Dissolved oxygen concentrations in blanketed transformer #2 as a function of blanketing time.

Dissolved gases (in the oil) that diffused into the gas space of the conservator were transported to the atmosphere by the constant flow of nitrogen. The concentrations of dissolved carbon dioxide and combustible fault gases also decreased. However, the concentrations of hydrogen, methane, carbon monoxide, ethane, ethylene and acetylene showed little variation after 8 years blanketing (see Tables III and IV).

During this period of time the dissipation factor of oil maintained its initial value of 0.48% at 100°C. In 2002, ATCO Electric successfully tested the system on a 144 kV, 40-MVA power transformer [20].

TABLE III. DGA RESULTS AFTER 8 YEARS BLANKETING OF TRANSFORMER #1.

Gas	Concentration (ppm)	
	Before N_2 blanketing	After 8 years
Hydrogen	3.3	<5
Oxygen	25859	1450
Nitrogen	57971	83257
Methane	1.4	2
Carbon Monoxide	<1	<25
Carbon Dioxide	738	191
Ethylene	3.3	1
Ethane	0.4	<1
Acetylene	<1	<1
Total Gas Content % v/v:	8.3	8.47

TABLE IV. DGA RESULTS AFTER 8 YEARS BLANKETING OF TRANSFORMER #2.

Gas	Concentration (ppm)	
	Before N_2 blanketing	After 8 years
Hydrogen	<1	<5
Oxygen	26583	1083
Nitrogen	58192	80484
Methane	1.5	2
Carbon Monoxide	<1	<25
Carbon Dioxide	775	200
Ethylene	3.1	<1
Ethane		<1
Acetylene	<1	<1
Total Gas Content % v/v:	8.4	8.15

These data confirm the theoretical assumption on which the trial was based, i.e., the dissolved oxygen in the oil is replaced by nitrogen, a chemically inert gas.

Figures 8 and 9 present absorbance curves for oil samples taken from the 5 MVA units before N_2 blanketing, and after 6 months and 8 years blanketing.

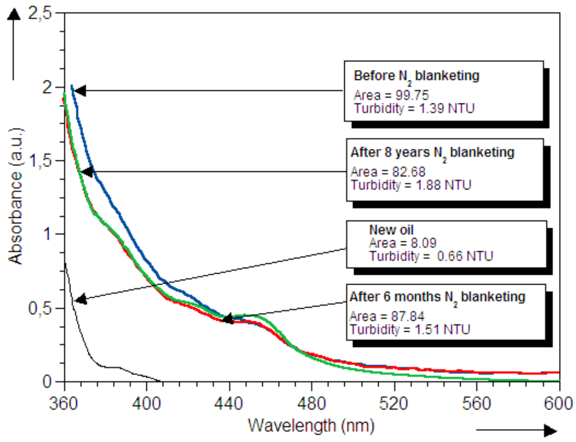

Figure 8. Variation of absorbance with wavelength, and turbidity, of oil samples from transformer #1.

The areas below these curves and the turbidity values are reported. Absorbance curves and turbidity values for a fresh oil sample ("new oil") are also reported. Tables V and VI, show that the total acid number (TAN), turbidity and DDP vary slightly with increasing blanketing time. However, the

DDF at 100°C increased substantially in both transformers, possibly due to free radicals becoming charge carriers.

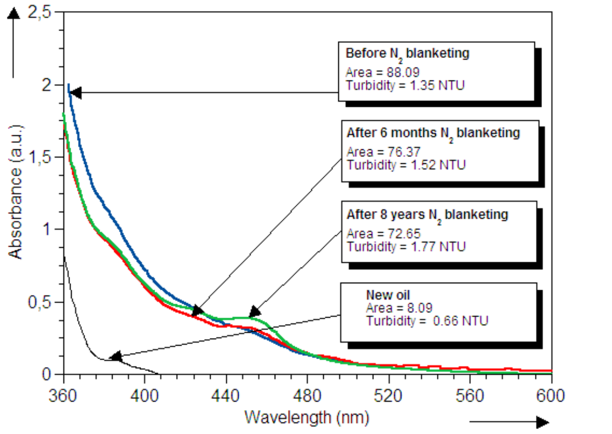

Figure 9. Variation of absorbance with wavelength, and turbidity, of oil samples from transformer #2.

TABLE V. TEST RESULTS FOR BLANKETED TRANSFORMER #1, AFTER 6 MONTHS AND AFTER 8 YEARS N_2 BLANKETING. IFT = INTERFACIAL TENSION, DDP = DISSOLVED DECAY PRODUCTS, TAN = TOTAL ACID NUMBER, DDF = DIELECTRIC DISSIPATION FACTOR.

TEST	TEST	UNITS	TRANSFORMER #1		
			Before blanketing	after 6 months	after 8 years
DDF at 100°C	D 924	%	-	0.356	0.973
Turbidity	D 6181	NTU	1.39	1.51	1.88
DDP	D 6180	Area*	99.75	87.84	82.68
TAN	D 974	mg KOH/g	0.034	0.026	0.022
Water Content	D 1533	ppm	-	-	16.9
IFT at 22°C	D 971	dynes/cm	-	-	32.3

* Integrated area under absorbance curve between 360 nm and 600 nm.

TABLE VI. TEST RESULTS FOR BLANKETED TRANSFORMER #2, AFTER 6 MONTHS AND AFTER 8 YEARS N_2 BLANKETING. IFT = INTERFACIAL TENSION, DDP = DISSOLVED DECAY PRODUCTS, TAN = TOTAL ACID NUMBER, DDF = DIELECTRIC DISSIPATION FACTOR.

TEST	TEST	UNITS	TRANSFORMER #1		
			Before blanketing	after 6 months	after 8 years
DDF at 100°C	D 924	%	-	0.452	0.817
Turbidity	D 6181	NTU	1.35	1.52	1.77
DDP	D 6180	Area*	88.09	76.37	72.65
TAN	D 974	mg KOH/g	0.023	0.026	0.03
Water Content	D 1533	ppm	-	-	13.5
IFT at 22°C	D 971	dynes/cm	-	-	32.6

* Integrated area under absorbance curve between 360 nm and 600 nm.

B. The removal of moisture

The dry, high purity nitrogen used to purge the headspace extracts moisture as well from the oil while simultaneously excluding air (oxygen) from the system. The flow of nitrogen through the dehydrating breather also removes moisture from the silica gel [17].

To assess the practicality of removing moisture using continuous flow purging of an oil surface, a brief laboratory procedure simulating the phenomena occurring under field conditions has been developed. Figure 10 shows a schematic of the equipment. A flow of 99.5% purity nitrogen at 28.3 litres per hour was maintained for 24 hours.

The results are summarized in Table VII. The moisture content of the oil was measured by Karl Fisher titration.

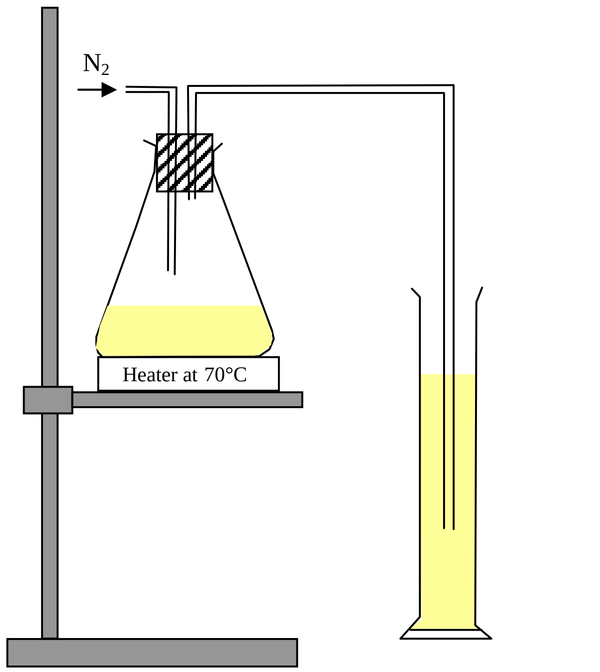

Figure 10. Laboratory set-up to reduce the dissolved water content of oil.

TABLE VII. MOISTURE CONTENT OF VARIOUS OIL SAMPLES, BEFORE AND AFTER NITROGEN FLUSHING.

	Initial Moisture content (ppm)	Final moisture content (ppm)
Mineral oil sample 1	11.6	5.1
Mineral oil sample 2	19	3
Mineral oil sample 3	48	5.4
Envirotemp® FR3™ Fluid [30]	90.7	6

C. Economic technical and Environmental considerations

In spite of the necessity of continuous supply of an inert gas, the nitrogen blanketing system described above has the following advantages:

(1) Since the nitrogen supplied by the membrane generator is moisture free and its flow is in one direction only, frequent changing of depleted silica gel in the air desiccators filters is no longer necessary.
(2) With the gradual removal of dissolved oxygen in the oil, secondary chemical reactions of the oil with the gases generated under the effect of electrical stress are impeded. Thus more reliable dissolved gas analysis (DGA) data are obtained, and they may therefore be interpreted with greater confidence.
(3) Fault gases can freely escape from the transformer.
(4) The extent of oxidation aging, especially in cellulose insulants, is greatly reduced as a result of decreased O_2^- and H_2O contamination. Expenses associated with oil reclamation and reconditioning may also be reduced.
(5) The use of antioxidant inhibitors may be unnecessary.
(6) The system is reparable in situ.
(7) Old transformers may be easily retrofitted.

(8) The life expectancy of aging transformers may be extended and their operational reliability improved, especially in the case of heavily loaded units.

(9) Currently, the reclamation of service-aged fluids is performed mostly by using Fuller's Earth (FE), because of its absorption selectivity for oxidized and ionized decay products. Usually this inexpensive material is used only once, and the depleted absorbent is discarded in landfills. Therefore a reduced requirement for FE in reclaiming aged oils will certainly enhance environmental protection.

VII. CONCLUSIONS

Accelerated aging tests were performed under controlled laboratory conditions, with and without oxygen inlet. The reported results convincingly prove that paramagnetic nature of oxygen can adversely affect the dielectric properties of liquid and solid insulations used in power transformers.

The outcome of an industrial experiment designed to evaluate a new nitrogen blanketing system for freely breathing transformers is presented. The experiment involved purging the oil surface in the conservator by a constant flow of pure nitrogen. Data obtained over an eight-year period clearly indicate that this innovative, environmentally friendly, and economically affordable technique can arrest or reduce the oxidation decay process of oil-paper insulation in freely breathing power transformers.

Rather than reconditioning or reclaiming service-aged oil to restore its initial properties, DOMRS makes it possible to maintain the initial physical and chemical properties of the insulating oil throughout the lifetime of a power transformer. The oxidation decay of oil-paper insulation will be hindered and the life expectancy of these expensive machines considered capital investments in every country infrastructure, extended, while the mineral insulating oil, a non-renewable resource, could be given a practically endless life expectancy.

VIII. REFERENCES

[1] Fofana, I. and Sabau, J. "Application of Petroleum-based oil in Power Transformers". "Natural Gas Research Progress", chapter 6, 23 pages, 2008 Nova Science Publishers, Inc. ISBN: 918-1-60456-700-7.

[2] T. O. Rouse "Mineral oil in transformers "IEEE Elec. *Insul. Mag., Vol*. 14, No. 3, 1998.

[3] ASTM Designation D 3612, "Standard Test Method for Analysis of Gases Dissolved in Electrical Insulating Oil by Gas Chromatography". Vol. 10.03

[4] I. Fofana, A. Bouaicha, M. Farzaneh, J. Sabau and D. Bussières, "Decay Products in the Liquid Insulation of Power Transformers", IET Electric Power Applications, Vol. 4, Iss. 3, pp. 177–184, 2010.

[5] Mayoux, C. "On the Degradation of Insulating Materials Withstanding Electrical Stress", IEEE Transaction on Dielectrics and Electrical Insulation, Vol. 7, October 2000.

[6] ASTM Designation D 6802, "Test Method for Determination of the Relative Content of Dissolved Decay Products in Mineral Insulating Oils by Spectrophotometry". Vol. 10.03.

[7] Industry News, "Punctured Rubber Bladders Detected by New ASTM Oil Test", Electrical Insulation Magazine, Jan/Feb 2006.

[8] ASTM D6181, Standard Test Method for Measurement of Turbidity in Mineral Insulating Oil of Petroleum Origin, Vol. 10.03.

[9] E. Briosso, I. Fofana, B. Robertson and J. Sabau, "Enhancing the Maintenance of Transformer Oils to Diminish the Risk of Blackouts", Energetica, Vol. 55, pp. 465-469, December 2007.

[10] J. Sabau, "Determination of solid suspensions in electrical insulating oils by turbidimetry", SAIT/CEA Technology Symposium, Calgary (Alberta), 11-12 June 1998.

[11] R. Sanghi, "Chemistry Behind the Life of a Transformer", Resonance, pp. 17-23, June 2003.

[12] I. Fofana, Y. Zié and M. Farzaneh, "Dielectric Response methods for diagnostic of Power equipments", In *Advance in Dielectric Material Research*, Chapter 6, pp. 249-299, Editor: Ai Huang, © 2009 Nova Science Publishers, Inc., ISBN: 978-1-60692-266-8 (https://www.novapublishers.com/catalog/product_info.php?products_id=8490).

[13] H. Z. Ding and Z. D. Wang, "On the degradation evolution equations of cellulose" *Cellulose*, pp. 205–224. 2008.

[14] G. Breen, on the behalf of Study Committee 12, "Essential requirements to maintain transformers in service", paper 12-103, *Cigre session* , Aug. 30 – Sept 5, 1992.

[15] H. Kan and T. Miyamoto "Proposals for an improvement in transformer diagnosis using Dissolved Gas Analysis' *IEEE Elec. Insul. Mag.* Vol. 11, N°6, pp. 15-21, 1995.

[16] ASTM D2440-99(2004) Standard Test Method for Oxidation Stability of Mineral Insulating Oil, Volume 10.03, Issued May 2007.

[17] J. Sabau, I. Fofana, A. Bouaicha, Y. Hadjadj and M. Farzaneh, "An Environmentally Friendly Dissolved Oxygen and Moisture Removal System for Freely Breathing Transformers", IEEE Electrical Insulation Magazine, Volume 26, No 3, pp. 30-38, May/June 2010.

[18] J. Fabre and A. Pichon, "Deteriorating processes and products of paper in oil. Application to transformers", CIGRE, Paper 137, pp. 1-18, 1960.

[19] United Sates Patent No. 7,208,874 B2 entitled "Method and Apparatus for Decreasing Gassing and Decay of Insulating Oil in Transformers". Inventor: Ioan Sabau, Alberta, CA Assignee: IonsOil Canda Ltd. Calgary, CA.

[20] ATCO Electric, "ATCO Electric Successfully Tests New Dissolved Oxygen Removal System", *IEEE Electrical Insulation Magazine Vol.* 22, No. 3, May/June 2006.