Journal of Energy and Power Engineering 6 (2012) 703-712

Verification of Insulation Oil Reclamation by Turbidity and Spetrophotometry Measurements

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Received: January 18, 2011 / Accepted: May 31, 2011 / Published: May 31, 2012.

Abstract: Oil reclamation with Fuller's earth is known to have an improved effect on conditioning aged oil. In this paper it is shown that aged oil reclamation effectiveness can be monitored with turbidity and spectrophotometry measurements. These low cost testing techniques offer a useful tool to quantify the effect of Fuller's earth. Experimental investigations performed in laboratory conditions have shown that the quality of properly reclaimed aged oil can compete with that of new oils. Thus, in addition to extending the life cycle of this non-renewable resource, on-line reclamation of liquid might also prevent the premature ageing of paper insulation. Studying the stability of reclaimed service aged oil samples emphasized the important role played by Fuller's Earth absorption capability.

Key words: Insulating oil, reclamation, Fuller's earth, turbidity, spectrophotometer, decay product, gassing tendency.

1. Introduction

Power transformers are important and one of the costliest equipments in electrical power transmission system. Their conditions have a critical influence on safety and reliability of the power system. Composite oil/paper insulation has been used in transformer for more than 100 years. These offer advantages of low material cost and ease of manufacture. Even though oil represents less than 5% of the total cost, it constitutes a vital part of the transformer body. Similarly to blood in a human being body, it keeps responsibility for the condition of the equipment. It is consequently now an established fact that the service reliability of power transformers largely depends upon the condition of the oil-paper insulation. While in service, both the liquid and solid insulation of windings undergo a slow but steady decay process. The ageing process is attributed to the decomposition of hydrocarbon molecules by either thermal or electric stresses (that originate from the design factors, operating conditions and electric transients) and the chemical aggressiveness of dissolved oxygen [1]. The breakdown of hydrocarbon chains generates not only soluble gases, as it is currently believed, but also colloidal suspensions. Impurities like acids, moisture, sludge, polar contents contaminate the oil. At present these impurities which are responsible for fast deterioration of oil and affect active service life of the transformer are removed by chemical treatment called reclamation. This procedure is economically attractive because of increasing prices for both mineral and synthetic transformer coolants, cost effective and environmentally sounds.

2. Background

Insulation oil used in power transformers consists of

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saturated hydrocarbons as paraffin and naphtene and can neither conduct current nor solute water. Oil conductivity depends on oil type and increases with aging by-products. Contaminants such as residues from refinery, pollution and particularly ageing/oxidation products enable the oil to conduct ionic current. Oil oxidation/degradation by-products are subdivided into soluble (dissolved) products and insoluble (suspended) products:

- The dissolved impurity particles are peroxide (R—OOR), alcohol (ROH), aldehyde (ROHO), ketone (RCO—R), organic acid (R-COOH), acid anhydride ($(RC(O))_2O$), organic peroxide (ROOH), ester (R—COO—R'), metallic soap ((RCOO) nM) (M means metal atoms), etc.;
- The suspended impurity particles include asphaltic sludge, soap, carbon, metals, cellulose fibers, dust, etc..

Oxidation by-products (peroxide gas, water soluble acids, low molecular weight acids, fatty acids, water, alcohols, metallic soap, aldehydes, ketones, lacquers, sludges of asphaltene) change the chemical make-up of the oil to allow more water to be dissolved [2].

The dominating contribution is made by carbonic acids, an ageing product of oil oxidation. Carbonic acid and water can dissociate to ions and hence increase conductivity considerably [3]:

$$\text{H-COOH} + H_2O \rightarrow \text{H-COO}^- + H_3O^+$$

H-CO is the aldehyde group of a carbonic acid.

Free electrons injected into the liquid insulation are accelerated by the electric field [4]. The collision of a fast electron with a hydrocarbon molecule M may be either elastic or inelastic [5].

Whereas stable molecules reaching their singlet excitation level (M*) usually release the absorbed energy as a quantum of harmless fluorescent light (hν):

$$M^* \rightarrow M + h\nu$$

vulnerable molecules (R-R') decompose and generate a pair of free radicals (R• and R'•):

$$\text{R-R'} + h\nu \rightarrow R\bullet + R'\bullet$$

Free radicals are believed to be central to the ageing of transformer oil insulation [6]. As their population increases, some gaseous or liquid fractions may capture a free electron and form an ion:

$$R\bullet + e^- \rightarrow R^-$$

The accumulation of such ionized molecules increases the dissipation factor of the insulation. Alternatively, large free radicals may recombine, leading to the formation of insoluble colloidal suspensions.

Electrical discharge under oil produces gases, carbon and free radicals. When discharges-by-products or oxidation-by-products accumulated in the oil ducts or at oil-paper interface, heat transfer will be very poor which result in paper overheating [5].

3. Aged Oil Condition Assessment Techniques

The insulating oil in a transformer becomes increasingly contaminated as the transformer ages in service. Contaminants include particulate debris from thermal, oxidative, or electrical degradation byproducts (sludge, acids, x-wax…) of oil or solid insulation, fibers, gases, moisture, etc.. Electrical and chemical techniques can therefore be used to assess the insulation electrical and the chemical properties respectively.

Transformer oil contains about 70% of diagnostic information. The variations in different oil characteristics may therefore be used to identify/detect the type of incipient failure in the transformer. Diagnostic effectiveness by oil tests may be subdivided into four groups [7]:

- Identification/characterization—parameters that can be used to identify/characterize the oil;
- Ageing rate—parameters/properties relevant to the ageing process;
- Dielectric properties—parameters characterizing the fluid as a good insulant. These parameters are also relevant to the dielectric safety margin;
- Degradation status—utilization of the oil as an indirect/non destructive diagnostic medium.

To meet pressing needs of power industry new maintenance technologies, especially new diagnostic tools are necessary. In recent years there has been considerable interest in the subject of life management of transformer equipment.

One can observe a fast developing economic based concepts and techniques as condition-based maintenance, reliability centered maintenance, and comprehensive life extension program, accompanied with on-line monitoring and on-line processing techniques.

In order to select a proper decision “What to do?” one ought to answer the question “What’s the real condition of the equipment?”. The easiest and the most accessible way to diagnose power transformer is to use transformer oil as efficient diagnostic media.

In spite of all the differences in their standpoints, the refiners, manufacturers and users have worked together. The development of several new laboratory testing procedures for mineral insulating oils over the past years has been the rewarding result of a cooperative work involving refiners, manufacturers and users, to produce mutually acceptable standard specifications for oil characteristics and test requirements. These testing focus all the important parameters that can be used to characterize oil (Fig. 1) [7].

An obvious sign of ageing is the change in the color of oil which changes from pale yellow to reddish brown. This color change can be measured by the technique of ultraviolet/visual (UV/Vis) spectroscopy [8] while suspended decay products can be monitored by turbidity [9].

The ASTM D 6802 method [8] is based upon the observation that in the range of visible spectrum all brands of new insulating liquids are almost completely transparent to a monochromatic beam of light. On the contrary, when the fluid contains decay products, the absorbance curve, as determined by a scanning spectrophotometer, significantly shifts to longer wavelengths. The numerical integration of the area below these absorbance curves permits measuring the relative content of Dissolved oxidation Decay Products (DDP: peroxides, aldehydes, ketones and organic acids) in the fluid samples.

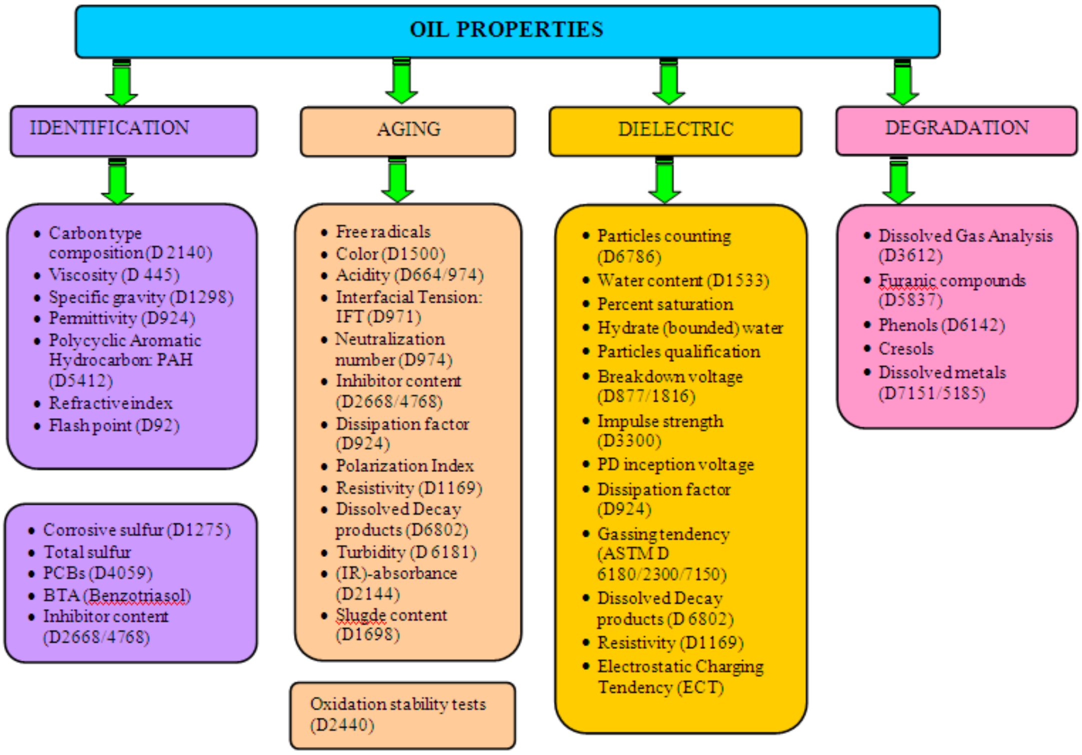

Fig. 1 Functional based classification of oil properties. Specifications in brackets are ASTM standards [7].

The ASTM D 6181 method [9] is an accurate optical laboratory technique developed to quantitatively determine the amount of microscopic solid suspension that may exist in both new and in-service fluids. A ratio turbidimetric optical system is used to measure the turbidity of insulating fluids relative to turbidity standards. Increasing turbidity signifies increasing fluid contamination (such as oxidation by-products). Other turbidity sources, such as water droplets or gas bubbles, are eliminated.

Unlike the color, the ASTM Designation D6802 allows the quantitative measurement of these harmful molecules (DDP) in real life as well as in laboratory conditions as shown in Fig. 2. Measuring the turbidity of oil by using the D6181 Designation, the real purity of liquid insulation can be reliably determined.

Even though in service conditions the amount of soluble and insoluble impurities is growing day by day, their amount is not reason for concern. While the TAN (total acid number) is still very small and the IFT (interfacial tension) is high, the paper insulation relentlessly adsorbs these trace impurities on its large surface, paving the way for the formation of incipient electrical failures. Therefore, the induction period is misleading. The result shown in Fig. 2 convincingly proves the sensitivity of these techniques.

Aged oils may be treated through three different processes [10]:

(1) Reclamation: The restoration to usefulness by the removal of contaminants and products of degradation such as polar, acidic, or colloidal materials from used electrical insulating liquids by chemical or adsorbent means. Reclaiming typically includes treatment with clay or other adsorbents.

(2) Re-refining: The use of primary refining processes on used electrical insulating liquids to produce liquids that are suitable for further use as electrical insulating liquids. This technique may include a combination of distillation and acid, caustic solvent, clay or hydrogen treating, and other physical and chemical means.

(3) Reconditioning: The removal of insoluble contaminants, moisture, and dissolved gases from used, electrical insulating liquids by mechanical means. The typical means employed are settling, filtering, centrifuging, and vacuum drying or degassing.

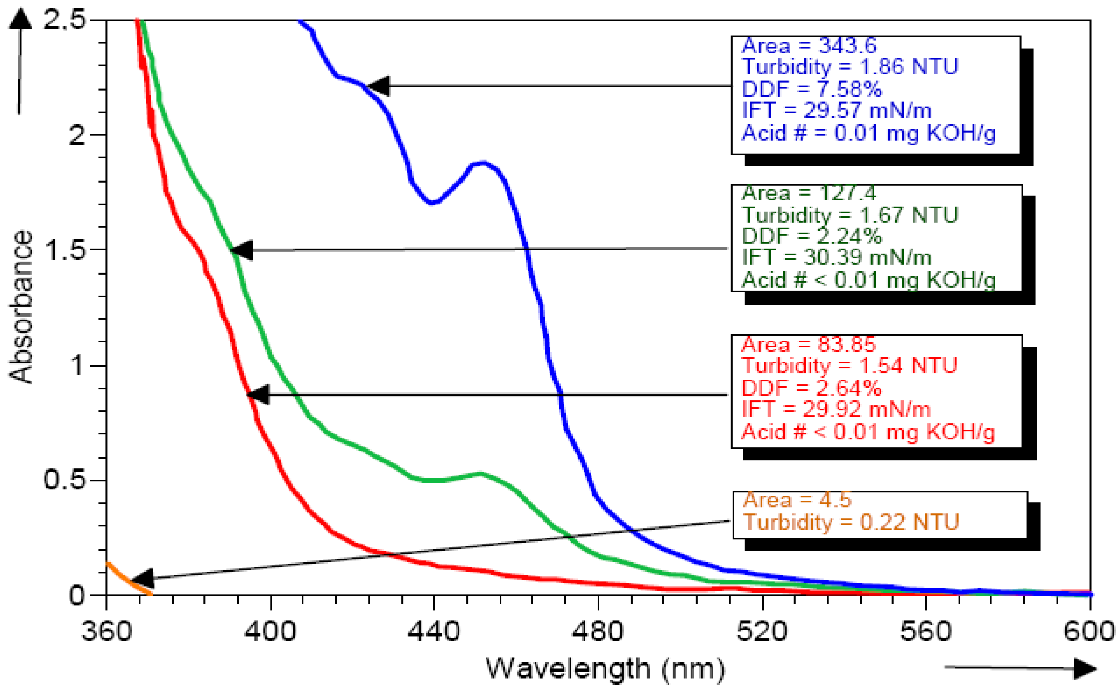

Fig. 2 Measurement of soluble oxidation decay products [5].

4. Aged Oil Reclamation

The reliability of oil-filled transformers is largely dictated by the ageing characteristics of the oil that involves a slow change in the physical and chemical properties of the oil. In general, decisions can be taken by the operator, based on analytical testing results. Maintenance solutions include refurbishment of the transformer or the replacement of the fluid. However, these treatments are expensive and a more cost effective option is to consider either oil purification or reclamation in order to rejuvenate the system before refurbishment becomes necessary [11]. The reclamation rejuvenates the transformer oil by eliminating contaminants formed due to entry of foreign particles, oxidation of oil and insulation deterioration, sludge formation, thermal cracking etc..

Transformer oils are frequently reclaimed through filtration. This may take the form of centrifuging, vacuum dehydration or absorption with FE (Fuller's earth) or another activated media. The reclamation of aged oils by Fuller's earth has long been practised by the electrical power industry. There is little up-to-date research published on the effects of Fuller's earth on transformer oil. Fuller's earth is a mined product (a clay type material with a composition of alumina, silica, iron oxides, lime, and magnesia in various proportions) which, after drying and processing by acid activation, is usually supplied as a fine powder. The colour can be grey, buff, green, brown or blue. Fuller's earth removes both moisture and neutralises carboxylic acids [11].

5. Experimental Investigations

In the laboratory made-plant, oil is heated at 60 °C when passing through the activated Fuller's earth cartridge to remove acids and impurities [12].

The diagram in Fig. 3 shows the progress of service-aged oil reclamation process with two different types of Fuller's earth, a normal one (FE 1) and an improved one (acid washed clay) referred as FE 2. Oil samples collected from a Canadian utility company ageing power transformers (47 MVA-161/26.5 kV, commissioned in 1984) were reclaimed in laboratory conditions. To provide based line measurement, tests were also performed on new oil of the same brand. The diagrams in Figs. 4 and 5 show the progress of the reclamation process after two passes of oil using the two types of FE.

The results indicate that the removal of dissolved decay products was not complete, even after two passes. Clearly the improved Fuller's earth (FE 2) shows a better capacity than the normal one (FE 1). Using this improved FE (Fig. 6) might require a reduced number of pass allowing reclaiming the transformer. Also, a reduced requirement for FE in reclaiming aged oils will certainly have a beneficial effect onto the environment.

Even though the major analytical properties of processed oil such as the dissipation factor, interfacial tension and total acid number may improve to the level of new oils, the quality of reclaimed oil can never regain the performance of new oil. As illustrated in Figs. 6 and 7, oil may be rejuvenated to the level of new one only after several passes.

An important side effect of oil decay product can be assessed by studying the gassing tendency under electric stress by measuring the rise of pressure of a sample of in-service deteriorated oil and reclaimed oil according to the ASTM Test Method D 6180 [13].

Oil sample reclaimed 15 times was submitted to electrical discharge according to ASTM D 6180. To provide baseline data for comparison, the same experiment was performed for new oil and the data are reported in Fig. 8. Determining the DDP and turbidity of the oil specimens before the D 6180 stability test (Table 1), and comparing the results with those obtained after the D 6180 stability test (Table 2), clearly show that reclaimed oil may compete with new ones.

Three different types of FE from various manufacturers were considered to reclaim the same service-aged oil. During the five-hour test, the pressure

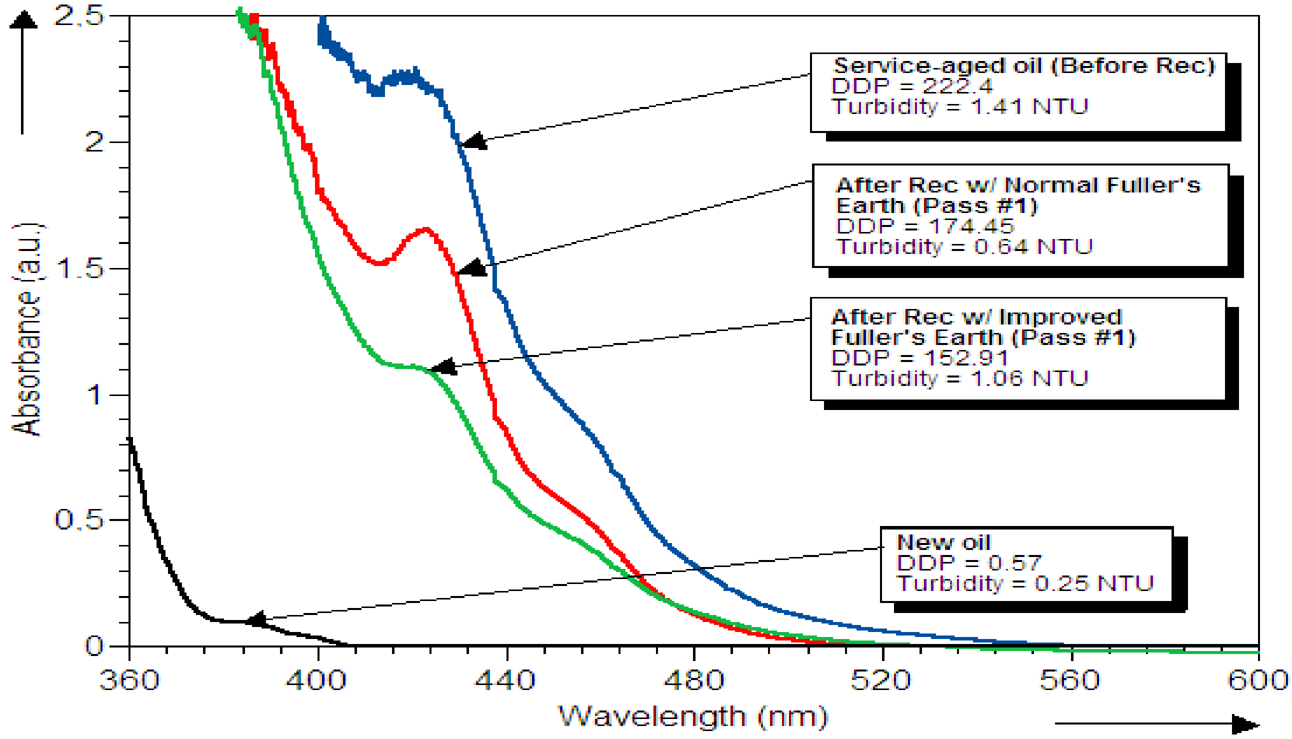

Fig. 3 **Absorbance curves of service-aged reclaimed with two different Fuller's earth oils compared with virgin oil.**

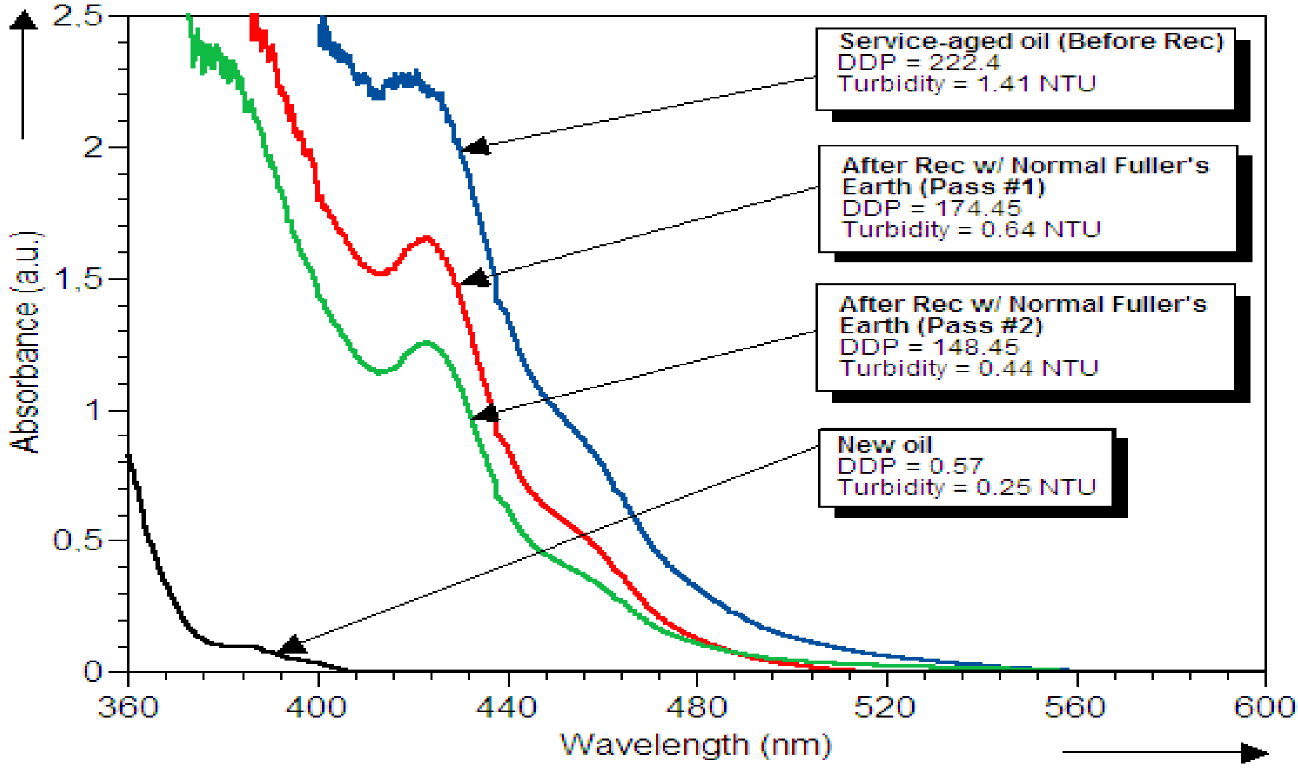

Fig. 4 **Absorbance curves of service-aged oil samples reclaimed with the normal Fuller's earth: effect of time on the reclaimed oil.**

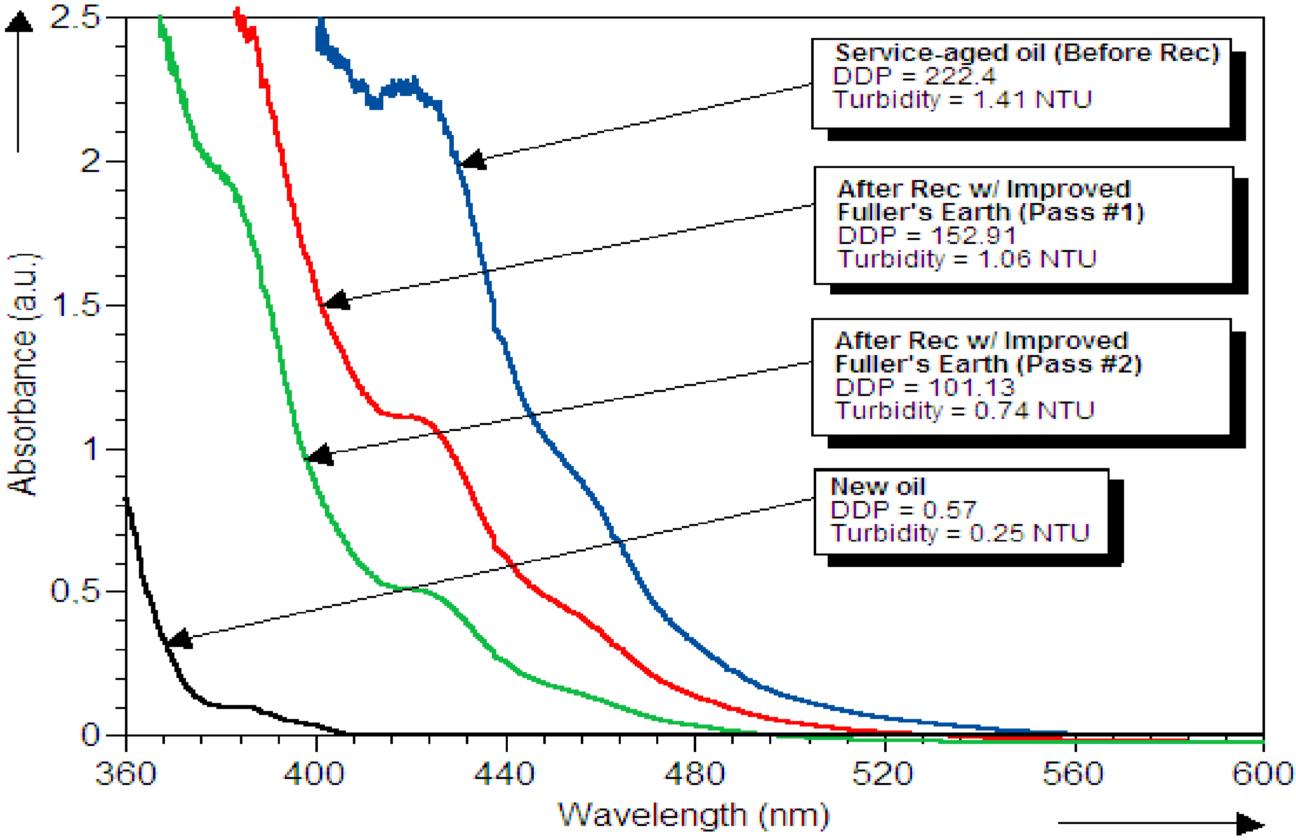

Fig. 5 Absorbance curves of service-aged oil samples reclaimed with the improved Fuller's earth: effect of time on the reclaimed oil.

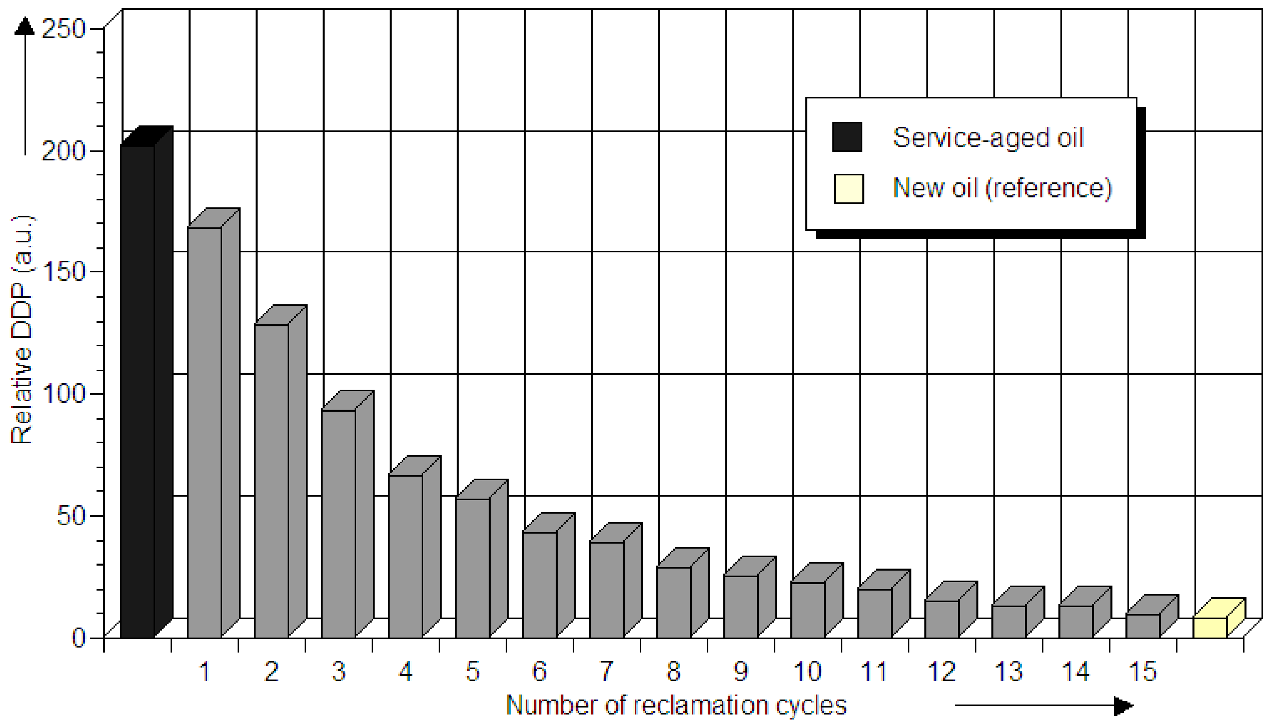

Fig. 6 Relative amount of the DDP (dissolved decay products) illustrating the effect of reclamation passes on oil quality.

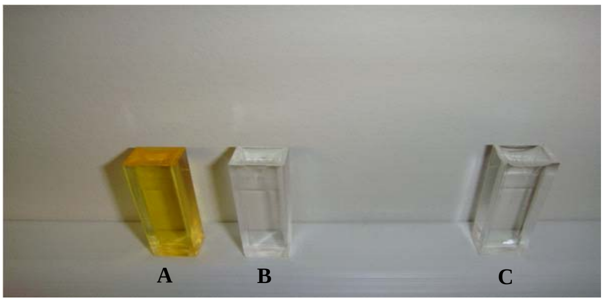

Fig 7 Qualitative comparison of oil samples: (A) service aged oil; (B) oil reclaimed after 15 passes and (C) new oil used as reference.

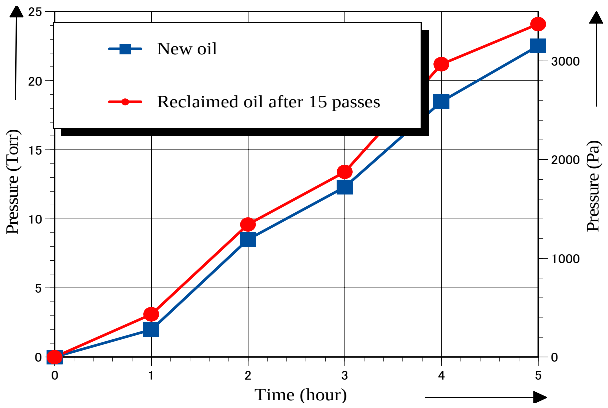

Fig. 8 Gassing tendency of new oil and reclaimed oil after 15 passes subjected to electrical discharge according to ASTM D6180.

Table 1 Oil samples assessment before D6180 stability test.

	New oil	Reclaimed oil after 15 passes
Water content (ppm)	27	28.4
Turbidity D 6181 (NTU)	0.6	0.54
DDP-D 6802 (area)	8.22	9.54

Table 2 Oil samples assessment after D6180 stability test.

	New oil	Reclaimed oil after 15 passes
Water content (ppm)	34.4	32.8
Turbidity D 6181 (NTU)	2.02	1.52
DDP-D 6802 (area)	28.14	30.52

increase inside the discharge cell was recorded (Fig. 9). Determining the DDF (dielectric dissipation factor), the DDP and turbidity of the oil specimens before the stability D6180 stability test (Table 3), and comparing the results with those obtained after the D 6180 stability test (Table 4), allow assessing the outcome of random secondary chemical reactions between large oil born free radicals [5].

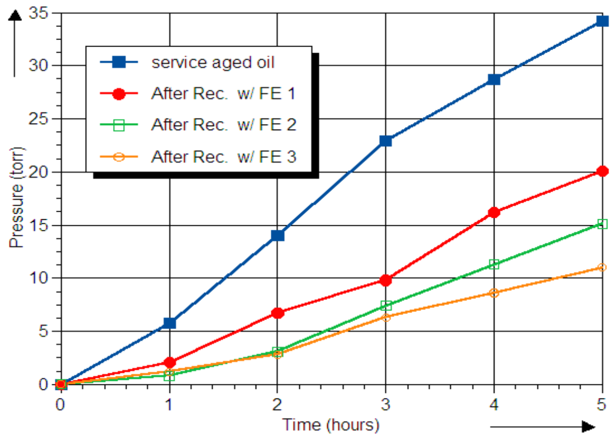

Fig. 9 Gassing tendency of aged oil and reclaimed aged oils subjected to electrical discharge according to ASTM D6180.

Table 3 Oil samples assessment before D6180 stability test.

	Aged oil	Recl. with FE 2	Recl. with FE 1	Recl. with FE 3
Water content (ppm)	32.4	23.9	14.7	21.1
DDF @50 Hz, 100 °C (%)	4.164	0.25	0.2576	0.1935
DDP-D6802 (area)	241.06	163.55	178.6	181.87
Turbidity D6181 (NTU)	1.62	1.34	1.6	1.22

Table 4 Oil samples assessment after D6180 stability test.

	Aged oil	Recl. with FE 2	Recl. with FE 1	Recl. with FE 3
Water content (ppm)	25.8	20.8	12.6	13.4
DDF @50Hz, 100 °C (%)	1.807	1.493	2.023	1.24
DDP-D6802 (area)	175.31	123.93	124.98	130.37
Turbidity D6181 (NTU)	2.37	1.99	2.16	2.47

The amount of gases evolved by an aged oil sample decreases after the selective removal of dissolved and insoluble decay products by reclamation. Hence, the selective removal capability of the FE on its gassing tendency might also be emphasized.

6. Economic and Technical Considerations

As oil ages in the transformer, it oxidizes and begins to degrade. Some of these byproducts attack the chemical bonds that hold the cellulose insulating materials (with a concomitant decrease in the degree of polymerization). Oxidation inhibitors are usually added to improve oil's oxidation stability but there are currently no procedures for restoring the thermal resistance of paper insulation. The thermal degradation of cellulose produces significant quantities of moisture that actively promotes further decomposition. The moisture significantly increases the power factor, may result in bubbling in the vicinity of hot-spots, and will increase the risk of electrical breakdown if it appears as free water in highly stressed regions. Since the life of a transformer is directly related to that of the insulating paper, action has to be taken quickly during the process of oil degradation. The experiment on oil reclamation clearly shows that the Fuller's earth is causing the improvements in the ageing indicators. To extend the transformer life, the accumulation in oil of compounds primarily responsible for the chemical changes that culminate in deterioration of the insulation system must be removed. With the removal of sludge, the oil and internal components of the transformer are cleaned of acids, chemical decomposition products, gases and moisture. The life expectancy of the unit is increased and lost productivity is kept to a minimum.

The anticipated benefits are reduced risk of dielectric breakdown blamed for over 75% of EHV (extra high voltage) power transformer failures and extended transformer life expectancy by retarding the cellulose aging processes [14]. Instead of disposing of (as scrap) oxidized mineral oils, a practically endless life expectancy could be given to this non-renewable resource by frequent reclamation.

7. Conclusions

UV/Vis spectroscopy and turbidity offer useful tools to quantify the effect of Fuller's earth. These fast, inexpensive and reliable laboratory testing procedures developed by ASTM (D 6802 and D 6181) have been used to monitor decay products in reclaimed oils as trace impurities. Determination of the absorbance curve and turbidity of aged oil before and after reclamation quickly and reliably determines the effectiveness of the purification technology. Confidence in this environmentally friendly procedure might thus be enhanced. As part of an overall maintenance strategy, these tests might help taking restorative measures before deterioration reaches a point where failure of the transformer is inevitable. It was not the intention of this contribution to suggest that reclaimed oils are equivalent to new oils; rather it seeks to expand the use of reclaimed oils to occupy the considerable volume for which they are entirely suitable. Consequently, the life expectancy of these expensive machines, considered capital investments in every country's infrastructure, can be extended, while the mineral insulating oil, a non-renewable resource, could be given a practically endless life expectancy.

Acknowledgments

The authors would like to thank Jaxon Filtration (United States) and Rio Tinto Alcan—division Énergie Électrique (Canada) for their support in materials. Thanks are also extended to Region Rhônes Alpes (France) for supporting the research stay of Dr. N'Cho in Canada.

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