USE OF NATURAL VEGETABLE OILS AS ALTERNATIVE DIELECTRIC TRANSFORMER COOLANTS

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ABSTRACT

This paper discusses the present efforts by researchers to develop and provide an alternative means of cooling and insulating transformers. These efforts are borne out of the obvious importance of transformers in electrical power supply network, and the present realisation that the existing method of cooling falls short of specifications. Most importantly, is the inability of mineral and petroleum oils to comply with environmental regulation laws. Natural vegetable oils have been found to meet the specifications since they have high flash points (300˚C), high fire points (250˚-300˚C), lower pour points (-10˚C) and have high dielectric breakdown voltage (>50KV). These are in conformity with standards like IEEE C57, IEEE 637, ASTM D6781 and IEC 60296. Their biodegradability make them safe for use in densely populated areas and close to waterways. This also makes them to be environmentally compliant and avoidance of sanctions from regulatory agencies. Since they are from renewable sources, their production and utilisation is simple and cost effective. Overall, this can ensure sustainable development.

This work has also measured the properties of palm oil against the IEEE C637, and ASTM D section for possible use as a dielectric fluid. The result shows that treated palm oil has break down voltage of 75 KV/mm, flash point (>220), fire point (>220) and moisture content (0.08%). Hence this has shown the potential of palm oil as a dielectric fluid. However future work should focus on further investigation before field application

Keywords : *Dielectric Fluids, Insulating Fluids, Palm Oil, Transformer Cooling, Transformer Oil*

INTRODUCTION

Transformers form an important part of an electrical network. Without them, utility companies would not be able to transmit and distribute electricity generated at remote power stations. Over time transformer failure can be costly not only to the utility or owner of the transformer but the consumer as well. Oil is used as an insulator and coolant in transformers and by monitoring its condition the transformer's overall health is determined. A typical transformer is shown in Figure 1.

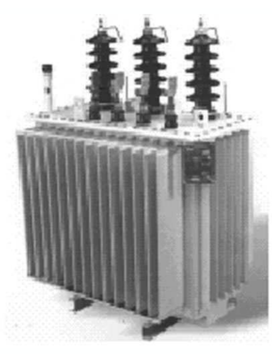

Figure 1: Typical power transformer

Electromagnetic devices like transformers heat up during operation because of resistive losses in their electrical and magnetic components. The rejection of heat is critical, since excessive temperatures can damage insulation, leading to failures. Failures of transformers cost millions of dollars to replace, require months to repair, and can leak toxic fluids. Cooling capability ultimately determines the amount of power that can be reliably handled by a transformer. As a result, transformers are designed to maximise heat rejection, and this often means bulky and expensive designs [1].

Transformer and even other electrical equipment generate heat during operation, therefore a coolant is necessary to dissipate this heat. The insulating oil fills up pores in fibrous insulation and also the gaps between the coil conductors and the spacing between the windings and the tank, and thus increases the dielectric strength of the insulation. Transformer in operation generates heat in the winding, and that heat is transferred to the oil. Heated oil then flows to the radiators by convection. Oil supplied from the radiators, being relatively cool, cools the winding. There are several important properties, such as dielectric strength, flash point, viscosity, specific gravity and pour point, to be considered when specifying certain oil as transformer oil. The quality of the oil is very important. At high voltages, highly loaded transformers demand better quality oils. While at low voltages, lightly loaded transformers, the demand for high quality oils is not critical [2].

For more than a century, petroleum-based mineral oils purified to "transformer oil grade" have been used in liquid-filled transformers. Synthetic hydrocarbon fluids, silicone, and ester fluids were introduced in the latter half of the twentieth century, but their use is limited to distribution transformers. Several billion litres of transformer oil are used in transformers worldwide [3].

The popularity of mineral transformer oil is due to availability and low cost, as well as being an excellent dielectric and cooling medium. Petroleum-based products are so vital in today's world that the consequence of its unavailability cannot be imagined transformers and other oil-filled electrical equipment use only a tiny fraction of the total petroleum consumption, yet even this fraction is almost irreplaceable [2].

Despite this obvious popularity, over time these oils have been found to be lacking in property requirement and most importantly is their negative environmental impacts. The natural vegetable oils, on investigation have shown impressive properties and stand as a good alternative or total replacement to mineral and petroleum oils.

AIM OF THIS WORK

The aim of this piece is highlight the efforts in transformer cooling and the developments of alternative dielectric fluids. The paper offers a summary of development work on a natural edible seed-oil-based dielectric fluid. It includes a background discussion of oils used, key properties comparison with other major dielectric fluid types, and details of field trials. Also this work has measured the properties of palm oil against the IEEE C637 and ASTM D section for possible use as a dielectric fluid.

HISTORY OF ESTER FLUIDS AS DIELECTRIC COOLANTS

In 1892, experiments with liquids other than mineral oils included ester oils extracted from seeds. None made operational improvement over mineral oil, and none were commercially successful. A particular problem with seed oil-based coolants was their high pour points and inferior resistance to oxidation relative to mineral oil [4].

Except for occasional applications in capacitors and other specialties, renewed interest in ester–based coolants did not occur until after the infamous issue of the PCB arose in the 1970's, coupled with the oil crises, which warrants the needs of renewable transformer oil. By then, there was the emergence of a mature synthetic organic ester industry serving the markets [5].

Depending on the type of acid and alcohol precursors, a variety of synthetic ester was possible. This allowed the industries to produce "designer" ester molecules. Synthetic aliphatic polyol esters were selected for askarel substitution in transformers because of their favourable viscosities/fire point ratios, and excellent environmental and dielectric properties. They are members of the same family of esters used for decades as jet engine lubricants.

The mid nineteen eighties saw the emergence of equipment and appliances using vegetable oils as insulating fluids.

In 1984, the first transformer applications of these synthetic esters were railroad rolling stock transformers with very high duty requirements. Due to their compact dimensions, such transformers had forced circulation flow to remote heat exchangers. Therefore excellent lubricity, very low pour point temperature, and a high fire point were important fluid characteristics for their application. Market acceptance of synthetic esters has limited to specialty applications, primarily due to their high cost compared to other dielectric fluids [6].

As a result of environmental regulations and liability risks involving non-edible oils, an extensive R&D effort, begun in 1990's, which led to revisiting the natural esters. They share many of the excellent dielectric and fire safety properties of synthetic polyol esters, and they are classified as edible oils. In addition they are biodegradable since they have organic composition and most importantly, they are much more economical than synthetic esters [7, 8].

THE PROBLEM

The mineral oils generate poisonous substances due to oxidative instability. The disposal and clearance after equipment failure or leakages is very difficult exercise. This is so, because of the need to comply environmental and safety regulations of authorities.

Most transformers and capacitors use a dielectric fluid based on Polychlorinated Biphenyls (PCBs). These products, although having fire-resistant and other properties required for use in electrical equipment, present some major disadvantages. These disadvantages are linked to the toxic nature of PCBs and their potential contamination with or transformation into dibenzo furans. Negative biological effects are now well established. Unfortunately PCBs have already been in widespread use for about 40 years in transformers and capacitors, and it is now necessary to put forward practical solutions for eliminating them wherever they are used. The first problem that countries with PCB transformers still in operation have to face is how to locate and identify this equipment. A decision will then have to be taken as to when, and how, the contaminated equipment will be managed reclassified and eventually eliminated [3].

Conventional Mineral Oils in Transformer Oils can pose threat to environment if spilled. Due to their negative environmental impact, their use is now banned in many countries. Silicon has a very high flash point (low flammability) and it is generally used in places where safety is highly desired. It is the most expensive oil and it is also non biodegradable [5].

CURRENT EFFORTS

In line with the myriad of problems stated above there is a need to look for alternative solutions. The solutions should not be restricted to manager, but be able to come up with alternative means of cooling electrical equipment. Along this line, bio or plant based oils are handy. In the past, vegetable oils have been used for edible and other domestic applications. Recent research works and industrial Research and Development have come up with an idea on usage of vegetable oils termed as "biogradable oils" which can find applications in industries. Engineering applications have been proven by several researchers.

There are two reasons why alternate natural sources of insulating fluids should be considered:

1. Transformer oil is poorly biodegradable. It could contaminate our soil and waterways if serious spills occur. Government regulatory agents are already looking into this problem and are imposing stiff penalties for spills. Many thousands of transformers are located in populated areas, shopping centres, and near waterways. Figures 2A and 2B show pole-mounted transformers near a coastal region, and pad-mounted transformers in a public area respectively [2].

2. Petroleum products (fossil fuels) are eventually going to run out, and there could be serious shortages even by the mid-twenty-first century. Conserving the petroleum reserves and recycling are vital for petroleum-based products - plastics, pharmaceuticals, organic chemicals, and so on. Until the development of economically viable alternate energy sources, there is no easy replacement for gasoline, jet fuel, and heating oil.Vegetable oils are readily available natural

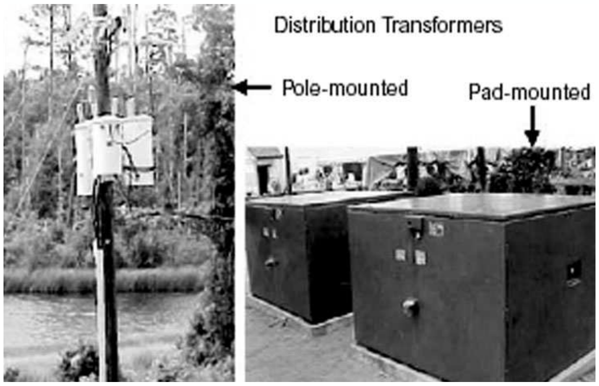

Figure 2: Mounting of outdoor transformer

products. They are used mostly for edible purposes, but special oils are used for drying and cutting oils. The only significant electrical use of vegetable oils suggested until the late 1990s were for power capacitors. Even they, the use is more experimental rather than commercial [3].

In the following section, a survey of the different kinds of products from vegetable sources used for dielectric coolants purposes will be presented. The aim is to identify the oils so far utilized and also to point out those that have already received full patents and are already commercially available.

PRODUCTION OF VEGETABLE TRANSFORMER OIL

As for the production, the vegetable dielectric coolants can be broadly divided into two:

a. Synthetic Esters

Synthetic ester dielectric fluids, most commonly ploy (pentaerythitol) esters, have suitable dielectric properties [5, 9] and are significantly more biodegradable than mineral oil or HMWHs. Their high cost compared to other less-flammable fluids generally limits their use to traction and mobile transformers, and other specialty applications.

Synthetic ester fluids have been used as a PCB substitute in compact railroad traction transformers since 1984 and in klystron modulators where their relatively low viscosity, high lubricity, and very low pour point properties justify the higher cost. Failure rates of traction transformers significantly decreased since replacing the askarels with synthetic poly esters.

The next is those available freely in nature and needs only some refining before application.

b. Natural Esters

Seed oil esters have been considered unsuitable for use in transformers, although past applications of rapeseed oil in capacitor applications hinted at considerable potential. Their susceptibility to oxidation has been a primary obstacle to utilisation as a dielectric fluid. However, modern transformer design practices, along with suitable fluid additives and minor design modifications, compensate for this characteristic [10].

The application of natural esters in transformers can achieve a balance of desirable transformer and external environmental properties not found in other dielectric fluids. Attractive sources of natural esters are edible seed-based oils. Used mainly in foodstuffs, these agricultural commodity oils are not only widely available, but unlike mineral oil, are derived from renewable resources [11, 12].

SYNTHESIS, PURIFICATION AND TESTING

The methods employed for testing is mostly ASTM [13] or IEC 60296[14]. In general the following are the required tests as per the two regulations and even others like ISO, DIN and some local regulatory and standardisation agencies:

Appearance, Colour and Colour number, Viscosity and Viscosity Index, Flash and Fire Points, Pour Points, Thermal Conductivity, Interfacial Tension, Dielectric Breakdown Voltage, Dielectric Constant, Dissipation or Power Factor, Acidity, Oleic Content, Moisture Content, Gassing Tendency, Neutralization Number, Oxidative Stability, Turbidity, PCB and Furan Content and Biodegradability Test. Most of the research works reported in this paper select the tests listed here.

The starting point in the production of vegetable oil based dielectric fluid is the vegetable seeds from trees. After separate of solid matter, the oil is treated with special solvents to remove unwanted components. Bleaching is usually done by clay filter presses, which further purify the oil. Deodorization by steam removes volatiles that produce odour. The RBD oil varies in electrical purity over a wide range, from marginal to impure; with conductivities ranging from 5 to 50 pS/m. For transformer use, it is desirable to have conductivity of 1 pS/m or below [3].

A conductivity meter, such as the Emcee meter described in ASTMD4308, may be used to monitor the purity of the oil. The final stage is the degasification and dehumidifying of the oil. Vegetable oils are hygroscopic; hence, they may absorb water at as much as 1200 ppm or more, at saturation and at room temperature. It is desirable to lower this to 100 ppm.

To stabilise the oil, it is necessary to add suitable antioxidants. Commonly used inhibitors such as DBPC and food-grade antioxidants are not powerful enough to produce an oil that will pass the ASTM D-2440 oxidation tests. A special antioxidant package that uses complex phenols and amines is used in the BIOTEMP® fluid. Care should be taken not to add too much because the conductivity would rise to unacceptable levels. It is desirable to keep the level of the additive component to below 1%. The approach used for the Envirotemp FR3® fluid is to avoid contact with air by careful sealing of the transformer and using an oxygen-scavenging powder above the oil level. The FR3 fluid does not pass the ASTM oxidation test because of its lower monounsaturate content, even with reasonable amount of inhibitors. The oxidation stability of vegetable oils is greatly dependent on the monounsaturate content, which should be over 80% for long-term transformer use [2].

Proper inhibitors are still needed. The percentage of tri-unsaturates should be negligible in these oils. The gel test is perhaps much more meaningful than the acidity values for vegetable oil after the oxidation test.

BIODEGRADABLE OILS

1. Reduced environmental impact, so in case of a spill, no hazardous chemicals would have to be cleaned up and they have less toxicity to living organisms.
2. They are safer, they have higher flash and fire points than most mineral based fluids in addition, their toxicity to organisms and humans is minimal.

3. The oils are of food grade in many cases, so they are easy to handle.
4. Reduced dependence on foreign oil, which gives the country preservation of foreign reserves.
5. Enhance economies in communities engaged in agricultural production, since the source is that of renewable resources.

The minimum health and environmental related requirements for applying a liquid as dielectric insulating fluid are:
- Non-toxicity
- Biodegradability
- Production of only acceptable and low-risk thermal degradation by-products
- To be recyclable and readily disposable.

These oils include Soya- bean oil, Sunflower oil, Coconut oil, Olive oil and oil extracts from the seed of Moringa Oliefera. The sunflower oil, which is 100% environmental friendly, is used as a transformer oil and for special purposes. In some countries, the oil has been proved to be able to sufficiently replace mineral oil, synthetic esters and silicon oils. Unfortunately the price of sunflower oil is very high when compared to mineral oil [7, 13].

The Nebraska Public Power District is exploring the use of soybean-based oil in electric transformers. Their product called Biotrans is earth-friendly, soybean-based transformer cooling oil. A standard distribution-system transformer is filled with this soybean-based oil, rather than traditional petroleum-based mineral oil. Biotrans transformers offer many benefits over conventional mineral oil transformers. It is biodegradable, in case of a spill or leakage; no hazardous chemicals need to be cleaned up. It provides an innovative new product for crops grown by farmers. It is safer than mineral oil, because of its higher flash point (ignition temperature). It offers a lower transformer lifecycle cost; no hazardous- waste disposal cost required, and it also has a potential recycling value of used soybean oil [14].

The properties of coconut oil, which is an indigenous product of Sri Lanka and other tropical countries, has been investigated, to decide whether it can be used as insulating oil in distribution transformers. An experimental 5-kVA transformer, filled with coconut oil has been constructed and investigated. The study has shown that coconut oil not only appears to possess the necessary electrical properties, but also is environmentally friendly oil and an indigenous resource of Sri Lanka. Thus considering the economic, environmental and social costs, the use of coconut oil for Sri Lanka has become a viable option [2].

An alternative transformer cooling fluid was developed from Indian beach oil in 2001. The beach oil is extracted from the Pongamia glabara tree and used for edible purposes. The tree is native to India and Sri Lanka, The oil was chosen for that work because of the initial good properties it possess The work came up with a transformer cooling oil called MEKO and its properties were compared with other oils like Midel 7131 and R. temp [10].

The researchers found that:
- Physical and chemical properties of MEKO are comparable to Midel 7131 and R.temp.fliud.
- Accelerated ageing studies performed on ester reveals that the Methyl ester is having more chemical stability even without inhibitor towards oxidation and the extent of ageing is less compared to mineral oil, Midel 7131 and Rtemp. Fluid.

Malaysia has the abundance of bio-gradable oils. The time is now ripe for the study into local resources to solve the problems of humankind locally, which encompasses a shift from environmentally hazardous resources, for the production of goods and services, to safe and environmentally friendly renewable resources The palm oil will be used for this work, it is an indigenous resource to Malaysia. The oil is also available in plenty so there is then the assurance of sustainability.

EXPERIMENTAL WORKS

The crude palm oil was filtered to reduce the level of impurities in the crude oil. Impurities can cause very easy occurrence of breakdown voltage. After the filtration, the samples were tested for turbidity using the ASTM D 6181.The turbid meter was for the measurement.

The ASTM D6871 standard regarding vegetable oils to be used for electrical equipment maintenance was followed in categorising the oil. The sampling was done according to ASTM D923 the breakdown voltage was measured using the ASTM D1816 and employing the 2.5 mm gap (0.08"). Figure 3 shows the voltage breakdown tester.

Figure 3: Dielectric breakdown voltage measurements equipment

Figure 4: Moisture analyser

As the break down voltage were observe, certain tests were performed to verify and have basis for explaining the level of break down voltage obtained from the ASTM D1816 test. The flash and fire points were performed using ASTM D92.The relative density were measured according to ASTM D1298, the viscosity was evaluated using the ASTM D88 and D445 and the viscosities were measured at 0˚C, 40˚C and 100˚C.

Other tests performed are the thermal conductivity according to ASTM D2717, the percentage moisture content according to ASTM D3277 and visual appearance according to ASTM D1524. Figure 4 shows the moisture analyzer.

RESULTS AND DISCUSSION

The results obtained from the experiment are presented here in tabular form. The comparison between the properties of other oils to the properties of palm oil were made.

Table 1 lists the results obtained, the breakdown voltage has a good correlation with the turbidity of the oil sample being tested. As it can be seen, the RBD palm oil has the lowest turbidity and its breakdown voltage came out to be the best i.e. up to 75KV/mm. While the crude form has a very high turbidity and the breakdown voltage was 23 KV/mm. This shows that if further purification could be carried on the crude palm oil, the turbidity could be reduced and hence raises the breakdown voltage.

Table 1: The properties of palm oil compare with mineral oil

Test name	Test Mthod	Limit	Oils Tested		
			RBDPO	CPO	Mineral
Turbidity NT at room temperature	ASTM D 6181	0.1-900	3.12	>900	0.535
Dielectric breakdown voltage at 50Hz VDE electrode 2.5mm gap in KV/mm	ASTM D1816/IEC296	30/50	75	23	45
Fire point min.°C	ASTM D92	200	>220	206	185
Flash point min.°C	ASTM D92	180	>220	195	145
Smoke point min.oC		150	200	180	140
Rlative Density 15° C/ 15° C Max.	ASTM D1298	0.96	0.9	0.87	0.89
Viscosity max.eSt at:	ASTM D 88/D445				
100°C		15	12		3
40°C		50	48.5		12
0°C		500	400		300
Thermal Conductivity (W(m/K)	ASTM D2717	0.2	0.17	0.16	0.123
Thermal Resistivity (m°C w^{-1})			5.98	6.16	
Thermal Diffusivity (mm^2 s^{-1})			0.1	0.1	
Visual Examination	ASTM D1524		Yellow	Red	Yellow
Moisture content in percentage	ASTM D3277	0.01	0.08	0.16	0.1

The other properties go in agreement that good properties ensure a good dielectric breakdown voltage of an insulating liquid. For example the moisture content of RBD palm oil is 0.08% and hence similar value for the break down voltage. Even though the limit should have been 0.01, but the break down obtained i.e. 75 KV/mm obtained for applications like transformers, where distribution transformers voltage is 11KV and 33KV. Even during fault where the voltage goes up to 2.5 times the nominal voltage this break down voltage is quite adequate.

Even though the mineral oil appears to have good turbidity, but still the breakdown voltage came out to be 45KV.This so because the moisture content of it is high (about 30%). So the crucial factors that affect the breakdown voltage are the amount of suspended particles and the moisture content.

The viscosity of a dielectric fluid is very important property; hence this property should be viewed differently. The operating temperature greatly affects the viscosity of a fluid. Inside the transformer tank, for example, the temperature varies considerably depending on the loading, ambient temperature and it rises excessively especially during faults. Table 2 shows the viscosities of RBDPO at different temperatures. It can be seen that at higher temperatures, the viscosity gets lower. This shows that there is an inverse relation between the viscosity and the temperature. For the smooth operation of the oil in electrical equipment, there is the need for the temperature to remain around the mid range.

The flash and fire points have shown that the oil can safely be used even where the temperature is expected to be very high; the limit expected for most applications is 100˚C. The appearance and the relative density are in agreement with the limit of the standard. The viscosity at different temperature shows suitability of the oil for dielectric use.

Table 2: The Viscosities of RBDPO At Different Temperatures

S/N	Temperature in˚C	Viscosity in (CS)
1	0	500
2	25	300
3	40	48
4	60	30
5	100	15

CONCLUSION

Today the world is witnessing the period of a shifting from the petroleum and mineral oils that are depleting and environmentally unfriendly in transformer cooling to vegetable oils that are renewable and environmentally friendly. These renewable resources have good dielectric properties and are compatible for use without any risk. The market and regulatory pressures to reduce liability risk exposure of mineral-oil-filled distribution and power transformers are increasing. In addition, there are demands to improve equipment efficiencies and adopt more "earth-friendly" options in our power systems. Considering these paradigm shifts, the industry has been developing new transformer concepts.

The properties of palm oil have been investigated against standards, and the results shows that the treated palm oil has a very good potential to be used as a dielectric fluid. The breakdown voltage, which is of paramount important to dielectric fluids, has been found to be adequate. The added advantages of vegetable oils in electrical equipment are that they have good biodegradability, which is well suited to palm oil as an organic natural ester. Hence the development and usage of dielectric fluid form palm oil base could ensure compliant to environmental and safety laws. ■

REFERENCES

[1] J. Maulbetch, *"Magnetic Fluids Could Cut Transformer Upgrade Costs"* EPRI Journal 1997, pp 68-72

[2] D.C Abeysundara , C. Weerakoon, Lucas, J.R., Gunatunga, K.A.I., and Obadage, K.C.*"Coconut Oil as an Alternative to Transformer Oil"*, ERU, Symposium Sri Lanka, 2001, pp1-11.

[3] T.V. Oommen *"Vegetable Oils for Liquid-Filled Transformers"* , IEEE Electrical Insulation Magazine, Vol. 18, No. 1, pp 7-11, 2002.

[4] A. C. Wilson, *"Insulating Liquids: Their Uses, Manufacture and Properties"*, London, U.K., Institution of Electrical Engineers, 1980.

[5] T.V. Oommen, *"Vegetable Oils for Liquid-filled Transformers"*, IEEE Electrical Insulation Magazine, No18, Vol.1, pp 7-11, 2002.

[6] T.V. Oommen, *"A New Vegetable Oil based Transformer Fluid: Development and Verification"*, Proc. CEIDP, Victoria, British Columbia, Canada, 2000, pp 308-312.

[7] E.W. Lucas, and K.C. Rhee, *"Animal and Vegetable Fats, Oils and Waxes."*, In Riegel's Handbook of Industrial Chemistry, 9th ed., J. A. Kent, New York: Van Nostrand-Reinhold, Ch.8, 1992.

[8] M. Shinke , M. Kenji, T.Toshiharu, T . Yasuo, N. Yoshitake, R. Shimizu, M. Kosaka and M.Wada,*"Fundamental Studies on the Development of Environmental Friendly Vegetable Oil Filled Transformer"*, Magazine of Insulation and Dielectrics IEE Japan January 2003.

[9] A. C Wilson M., *"Insulating Liquids: Their Uses, Manufacture and Properties."* Stevenage, U.K.: Peregrinus, 1980.

[10] C. Patrick Mcshene, *"Relative Properties of the New Combustion - Resistant Vegetable-Oil-Based Dielectric Coolants for Distribution and Power Transformers"*, IEEE Transactions on Industry Applications, Vol. 37, No. 4, July/August 2001.

[11] C. Patrick, McShane and T.V. Oommen, *"Ester Transformer Fluids"*, IEEE/PES Transformers Committee Meeting 7, Charles Tanger, Cargill October 2003.

[12] W. Morse, *"Preventive to Predictive; The Future of Transformer Oil Testing"*, AVO New Zealand's ,2001 International Technical Conference, April 2001.

[13] *"ASTM Annual Book of Standards, 2003 Section Ten, Electrical Insulation and Electronics."*, Electrical Insulating Liquids and Gases, Vol. 10.03, 2003.

[14] IEC Publication 296: *"Specification for Unused Mineral Insulating Oil for Transformers and Switchgear"* (incorporating Amendment 1:1986), 1982.