

INVESTIGATION OF DEPOSITS IN OIL-INSULATED SYSTEM BY INFRARED SPECTROSCOPY AND FERROGRAPHIC ANALYSIS

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ABSTRACT

In this paper a study on the transformer oil deposits has been carried out by infrared analysis and ferrographic inspection. Deposits could accumulate on different locations such as transformer coil surfaces, bottom, surfaces of the tank and contacts of tap changer. The results showed that the location at which deposits accumulate has a great influence on their constituents. The study of the physical and chemical properties revealed that deposits have higher water content, total acidity and ash content than the corresponding transformer oils. Depending only on the transformer oil characteristics to estimate or measure those of paper/oil insulation system in presence of deposits may not be adequate. The functional groups of deposits may not be sufficient to determine the additive needed to eliminate or remove such deposits. Ferrographic inspection indicated that deposits contain metallic particles, dust, transformer oil, solid and paper insulation degradation compounds. Oil flushing on transformer internal surfaces could be used to remove deposits. The size of solid particles in deposits has been determined to help in specifying the fineness of filters needed for filtration of flushing oil.

Keywords: Transformer oil, Infrared analysis, Ferrographic analysis, Oil insulation

INTRODUCTION

Recent investigations have been devoted to the development of diagnostic techniques for detection and identification of internal faults in transformers [1-3]. Development of in-service direct measurement of moisture in oil/paper insulated electrical equipment is being under consideration [4]. Formation of deposits and the rate of accumulation may affect these diagnosis and accuracy of such diagnostic and measurement techniques. Deposits will also reduce transformer cooling and may contribute to the heating of transformer oil resulting in further degradation [2]. Therefore, inspection of the constituents of deposits may aid in taking measures to prevent their formation and understanding the oil/paper insulation degradation mechanism. Wahab *et al.* [5] studied the metallic constituents of deposits and the effect of deposits concentration, as

contaminants, on the transformer oil breakdown voltage. The main objective of this paper is to study the effect of the location at which deposits accumulate on their ingredients and particle size. Infrared analysis and ferrographic inspection and analysis were employed to identify, distinguish and determine deposits constituents and dimensions of the main particles. The results of this study may help in determining the action needed to minimize the deposits either by using special additives or by using special oil flushing technique on the transformer coils.

EXPERIMENTAL WORK

Transformer Oils and Deposits Samples

Four in-service transformers have been considered in this study. Their oils are given the designations 'A', 'C', 'D' and 'E'. Deposits are found in different parts of these transformers. Four samples of deposits

have been collected from the transformers whose oils are 'A', 'C', and 'D'. These deposits are given the designations 'DA', 'DA*', 'DC' and 'DD'. The part at which deposits were found is given in Table 1. These locations are the most probable for deposit formation. Characteristics of transformer oil 'E' which is used and purified are considered as a base for comparison.

Transformer Oil Breakdown Voltage

The breakdown voltage of a transformer oil sample has been determined according to IEC 156 specifications [6]. The apparatus used is PGOS-3 BAUR with automatic voltage rising up to 75 kV. The rate of voltage rising is 2 kV/s and the electrodes have spherical shape of 13 mm diameter. The spacing is adjusted to be 2.5 mm. Testing starts with 3 minutes stand time and breakdown events are separated by intermediate stir time and stand time of 1 minute each. According to IEC 156 test the breakdown events are repeated 6 times then the average of the breakdown voltage values is obtained and given as the breakdown voltage test result in kV.

Total Acidity

Determination of the total acidity is a chemical neutralization process. The procedure of testing is given in IP 139/164 standards [7].

Water Content

The apparatus used to determine the water content in particle per million (ppm) is an automatic Karl Fischer Titration. The test procedure is according to IP 356/87 standards [8].

Ash Content

The ash content is given as a percentage in certain volume. The procedure to evaluate the ash content of a transformer oil sample is given in Reference 9.

Viscosity

The viscosity is determined according to the procedure given in ASTM designation [10].

Ferrographic Inspection of Deposits

Ferroscope is a microscope used for studies on particles on a ferrograph. The standard ferrograph consists of a pump to deliver sample at a certain flow rate, a magnet that develops a high-gradient magnetic field near its poles and a treated transparent substrate on which solid particles are deposited [11]. The sample is diluted with a special solvent (Carbon Tetrachloride) to promote the precipitation of solid particle. The magnetic particles adhere to the substrate and distributed according to their size. Under the bichromatic ferroscope, the entire ferrogram should be quickly scanned for overall impressions. With bichromatic light and a certain magnification (400), all the metal particles can be quickly identified. A number of ferrous and non-ferrous materials can be identified by various lighting.

RESULTS AND DISCUSSION

Physical, Chemical and Electrical Characteristics of Transformer Oils and Deposits.

Table 1 shows the measured values of the physical, chemical and electrical characteristics of the transformer oils and deposits. The table shows that the total acidity of deposits is affected by the locations at which they are formed. For example, the total acidity of deposits 'DA' and 'DA*' are 0.32 and 0.22 mg KOH/g oil respectively. The difference in deposits total acidity may be due to the interaction between the materials on which deposits are formed and the initially deposited compounds (layers). These materials may be iron, copper, cellulose or solid insulation for tank, contacts of tap changer, paper insulation and tap changer supporting solid insulation. It is important to indicate that the total acidity of the deposits which are collected from the coil surface is higher than that obtained from deposits at the bottom of

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the tank. This may be due to the higher temperature at the top of the transformer oil around the coils and the presence of bare terminal conductors (copper conductors) which act as a catalyst for transformer oil oxidation and acids formation. Paper insulation of transformer coils affects the properties of transformer oils and deposits. Acidity and water content, among other factors, affect paper ageing and degradation products [12]. As the paper gradually deteriorates with time, water, acids and polar groups are produced [13]. Therefore the presence of deposits on the coil surface

with higher values of total acidity than those of transformer oils partially may be resulted from paper degradation. Thermal degradation of cellulosic materials in paper insulation system produces furans [14] and their concentration in oil can be used as an indication of paper ageing [15]. The presence of deposits may affect the production of such compounds and give inaccurate information about paper ageing. Also, the effect of deposits on the electric field may in turn impose substantial changes on the course of paper degradation.

Table 1 Physical, chemical and electrical characteristics of transformer oils and deposits.

Property	Tr. A	DA	DA*	Tr. C	DC	Tr. D	DD	Tr. E
BDV (kV)	25	----	----	42	----	18	----	74
Water content (ppm)	63	----	85	28	----	65	----	8
Total acidity mgKOH/g oil	0.2	0.32	0.22	0.09	0.196	0.11	0.294	0.006
Ash content	Nil	0.11	0.17	Nil	-----	Nil	<0.1	Nil
Viscosity Engler	1.68	-----	1.8	1.6	-----	1.56	-----	1.6
Flash point	141	-----	140	146	-----	142	-----	154
Period of service Years	36			10		36		used and Purified.
Spec. gravity	0.8773		0.878	0.882	-----	0.879		
Location in Transformer		Coil surface	Tank Bottom		Sides of tank		Over core	

Ash content in transformer oil deposits is higher than that of the transformer oil itself. Ash content gives an indication of the presence of any ash forming materials. These materials may be insulation debris, fibers and other contaminants intruded into the transformer from atmosphere, transformer oil container or tank. As seen from Table 1 deposits have ash content although the corresponding transformer oil has not. This may be due to the process of depositing of ash charged producing materials under electric stresses. The value of ash content of deposits 'DA*' is higher than that of 'DA' in spite that they are obtained from the same transformer but from different locations. This may be due to the fact that the deposits (DA*) may be formed initially at the bottom of the tank or they are formed within compounds of high density and dropped to the bottom of the

tank. Under thermal and electrical stresses, the materials forming ash content of deposits 'DA*' may be subjected to some processes such as water absorption or adhesion to metallic particles resulting in an increase in their densities.

Table 1 shows that water content of deposits 'DA*' is higher than that of transformer oil 'A'. This may be due to the higher values of ash content in the deposits 'DA*'. As ash content may be produced from certain materials soaked with water. Water content can be produced in transformer oil for different reasons such as oxidation and chemical reactions [16]. Absorbed water can be released to the transformer oil from cellulose insulation during thermal excursion and product water can be freed by cellulose degradation during service ageing [17]. Measurement of insulation water content [4] may be affected by the rate of

formation of deposits on the insulation because the deposits may affect moisture content in paper insulation as previously indicated. Continuous monitoring of deposits formation may be effective in predicting paper/oil degradation. As seen from Table 1 the transformer oil breakdown voltage is greatly affected by water content, total acidity and service period. It can be concluded that depending only on the transformer oil characteristics to give an exact indication of water content in the insulation or give indication of paper/oil insulation system degradation in presence of deposits may not be adequate. Therefore continuous elimination of these deposits or removal of them may be beneficial from the view point of insulation properties.

Infrared Analysis of Transformer Oil Deposits

Infrared analysis of transformer oil 'E'

The infrared spectrum of an used and purified transformer oil 'E' is shown in

Figure 1. Infrared spectroscopy can detect the oxidation products of mineral oils between 1660 cm^{-1} to 1775 cm^{-1} and the ageing of the oil in service can be monitored, whether inhibited or not, by measuring the absorbance at 3650 cm^{-1} and 1710 cm^{-1} [18]. The main functional groups which can be detected from the infrared spectrum of transformer oil 'E', shown in Figure 1, are given in Table 2 and identified by alphabetic designations. Their concentrations can not be detected by such analysis. Figure 1 and Table 2 will be used as a reference for comparison between the results of deposits and transformer oil analyses. Only the differences in the functional groups between transformer oil and deposits will be reported in order to indicate the appearance or formation of pollutants in deposits. It should be pointed out that infrared spectroscopy data is often insufficient for complete identification of an impurity [18].

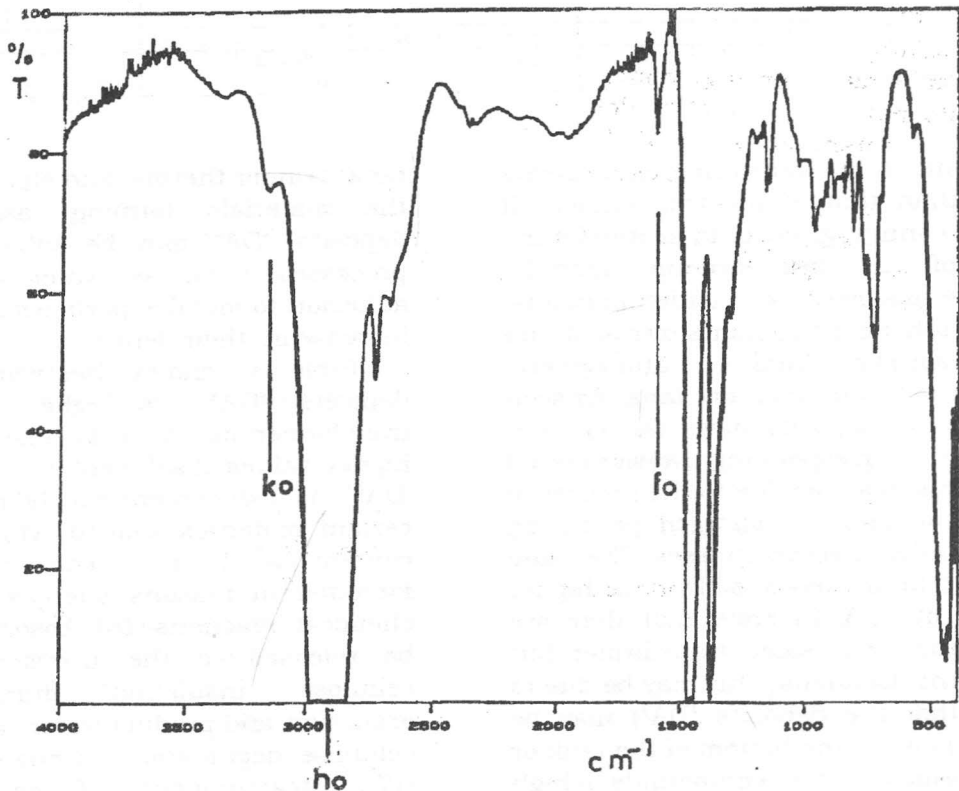


Figure 1 Infrared spectrum of transformer oil 'E', its functional groups are given in Table 2.

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Deposits 'DA'

These deposits are collected from the top surfaces of the transformer coil. Infrared spectrum of deposits 'DA' is given in Figure 2. The functional groups of this spectrum are given in Table 3. Comparing Figure 1 with Figure 2, it can be seen that there are some differences between the two figures. A comparison between Tables 2 and 3

indicates the major differences in the functional groups. From Figure 2 presence of moisture, vinyl, oxidation inhibitor, nitrogen compounds and hydrocarbon combined with metals can be detected. Silica and dust also appeared in the figure which may be intruded into the transformer from the atmosphere.

Table 2 Functional groups, wave number and wave length of transformer oil 'E' corresponding to Figure 1

Peak	Type of Vibration (Groups)	Wave number (cm ⁻¹)	Wave length (μm)	Intensity *
Ko	Unsaturated CH	3000-3100	2.74-2.79	(V,SH)
Ho	Aliphatic CH	2962-2853	3.4-3.5	(M,S)
fo	Aromatic C=C	1600-1580	6.3-6.3	(V)

* S=Strong, M=Medium, W=Weak V= Variable and SH= Sharp

Table 3 Functional groups for transformer oil deposits Figures 2-6

Peak	Type of Vibration (Groups)	Wave number (cm ⁻¹)	Wave length (μm)	Intensity
m	Alcohols and phenols (Free OH)	3650-3590	2.74-2.78	(M)
l	Aromatic CH	3100-3050	3.2-3.28	(S)
k	Aliphatic CH	3000-2850	3.33-3.51	(S)
j	Cyano(C≡N)	2200-2260	4.5-4.4	(M)
i	Aromatic C=C	1600-1450	6.25-6.9	(M,W)
c	Sulphur compounds S=O (Sulfoxide)	1070-1050	9.35-9.71	(S)

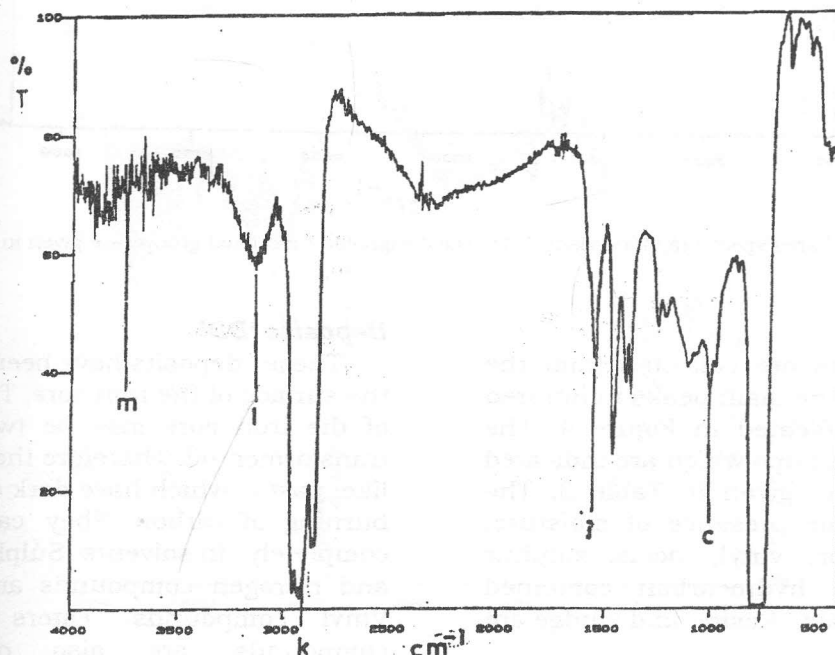


Figure 2 Infrared spectrum of deposits 'DA', the identified functional groups are given in Table 3.

Deposits 'DA'

The infrared spectrum of these deposits are given in Figure 3. The main functional groups are given by alphabetic designations in Table 3. The main differences in the functional groups between the transformer oil 'E' and deposits 'DA' can be detected by comparing Table 2 with Table 3. The infrared

spectrum of these deposits indicates the presence of nitrogen compounds. Also complicated hydrocarbon in connection with some metals such as iron and copper. Resin, burned carbon and esters can be detected. Sulphur compounds are also present besides oil oxidation inhibitor.

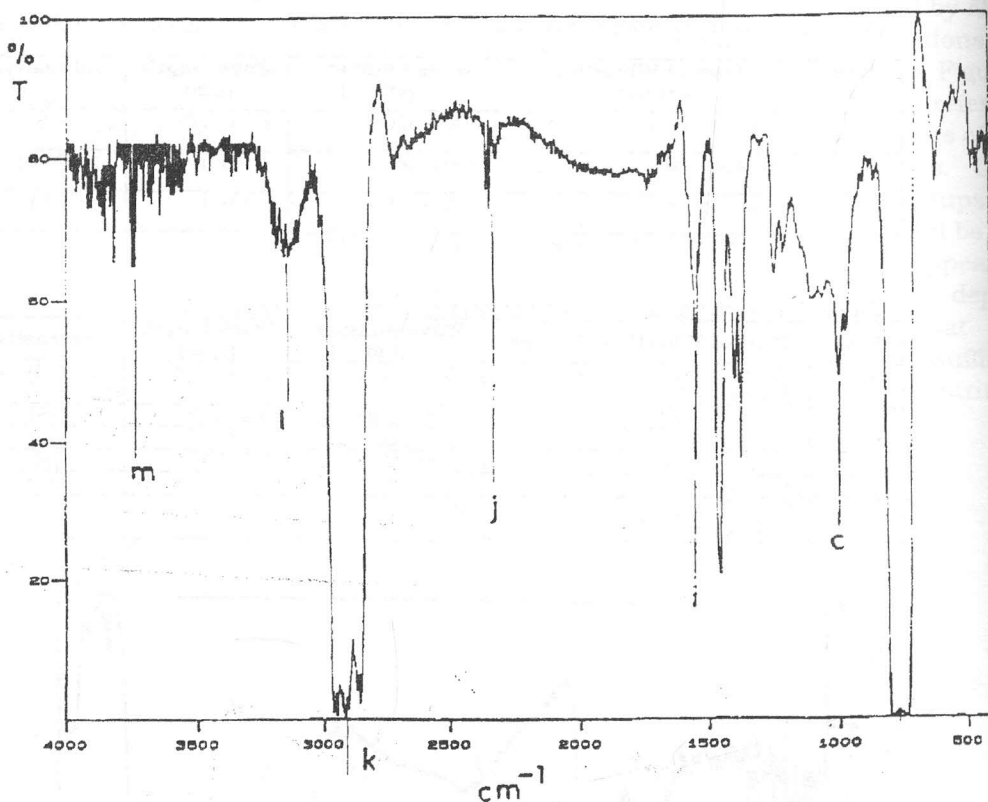


Figure 3 Infrared spectrum of deposits 'DA', the designated functional groups are given in Table 3.

Deposits 'DC'

These deposits are collected from the sides of the tank. The main peaks in infrared spectrum are indicated in Figure 4. The main functional groups which are indicated by alphabetic are given in Table 3. The figure indicates the presence of moisture, oxidation inhibitor, vinyl, acids, sulphur compounds, and hydrocarbon combined with some minerals. Resin and sludge are also detected.

Deposits 'DD'

These deposits have been collected from the surface of the iron core. The temperature of the iron core may be twice that of the transformer oil. Therefore these deposits are like paste which have dark color due to the burning of carbon. They can not be solved completely in solvents. Sulphur compounds and nitrogen compounds are also present. Vinyl compounds, esters and metallic compounds are also observed. The functional groups of these deposits are given in Figure 5 and Table 3.

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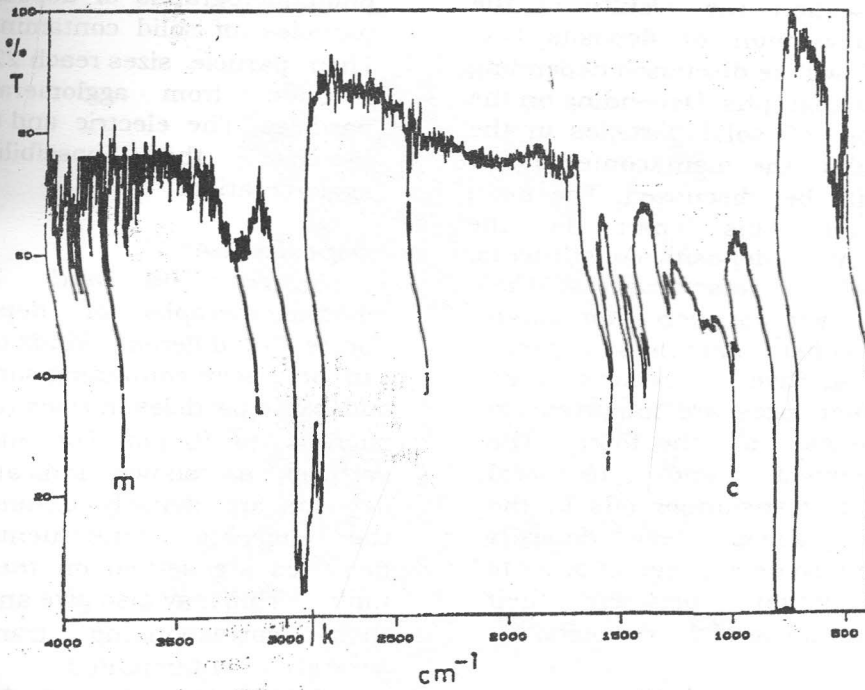


Figure 4 Infrared spectrum of deposits 'DC', its marked functional groups are given in Table 3

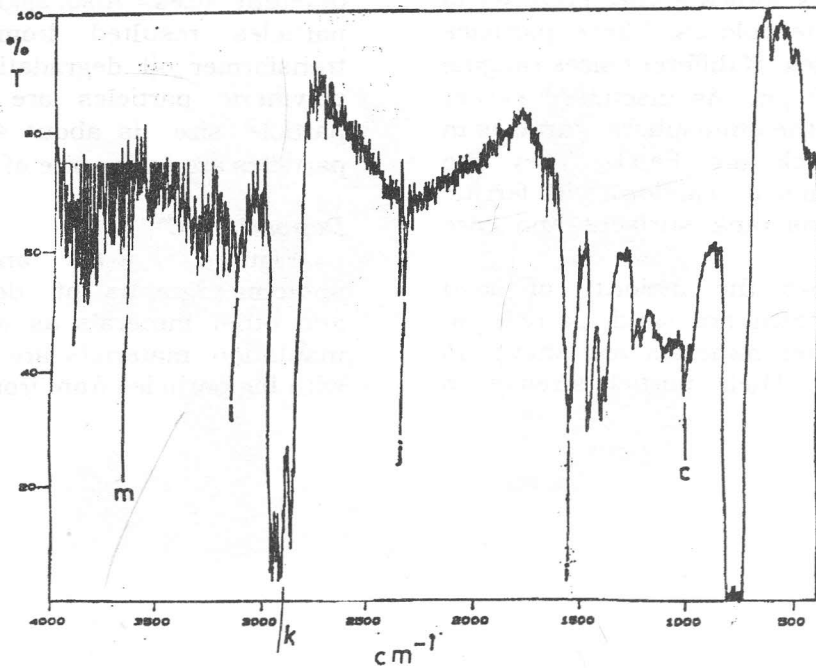


Figure 5 Infrared spectrum of deposits 'DD', whose functional groups are given in Table 3.

Results of Ferrographic Analysis

In this section the results of the Ferrographic inspection of deposits 'DA', 'DA*' and 'DC' will be discussed depending on the photomicrographs. Depending on the colour variation of solid particles in the photomicrographs the main contents and dimensions will be discussed. The main contribution of this part is the determination of deposits constituents, their sizes and the disclosure of their dependence on their location of formation. The materials of constituents help to specify a solvent or additive to remove such deposits and their sizes are important to specify the fineness of the filter. The physical, chemical and electrical characteristics of transformer oils in the transformers at which these deposits accumulated are also determined in order to clarify the relation between their characteristics and those of the deposits.

Deposits 'DA'

Figures 6-a, 6-b and 6-c illustrate the photomicrographs of deposits 'DA'. From Figure 6-a it can be seen that the photomicrographs indicate the presence of particles in white colours. These particles are sand particles of different sizes ranging from 10 to 100 μm . As discussed earlier their source is the atmosphere. Particles in brown and black are Fe_2O_3 . They are resulted by chemical reaction with ferritic elements such as tank surfaces and core laminations.

In Figure 6-b the majority of solid contaminants shown are sand particles in white. Some other minerals are shown in brown and blue. Their particle sizes reach 50 μm .

Figure 6-c includes other photomicrographs of deposits 'DA'. Very big particles of solid contaminant are shown. Their particle sizes reach 220 μm . They are resulted from agglomeration of small particles. The electric and thermal stresses increase the possibility of such agglomeration.

Deposits 'DA*'

Figures 7-a and 7-b show the photomicrographs of deposits 'DA*'. In Figure 7-a different kinds of solid particles can be seen containing sand, free metallic and oxide particles in sizes ranging from few microns to 50 μm . The intensity of such particles as shown indicates that these deposits are densely contaminated. Most of the deposits constituents with large densities are settled on the bottom of the tank. This may also give an indication that their corresponding transformers are severely contaminated. In this case, removal of these deposits by a solvent or flushing by transformer oil and fine filtration system should be recommended.

Figure 7-b shows sand particles of different sizes. Also, agglomeration of small particles resulted from insulation and transformer oil degradation as well as some polymeric particles are illustrated. Their particle size is about 45 μm . Iron oxide particles are in the size of 70 μm .

Deposits 'DC'

Figures 8-a and 8-b show photomicrographs of deposits 'DC'. Sand and other minerals as well as debris from insulation materials are shown associated with big particles from iron oxide.

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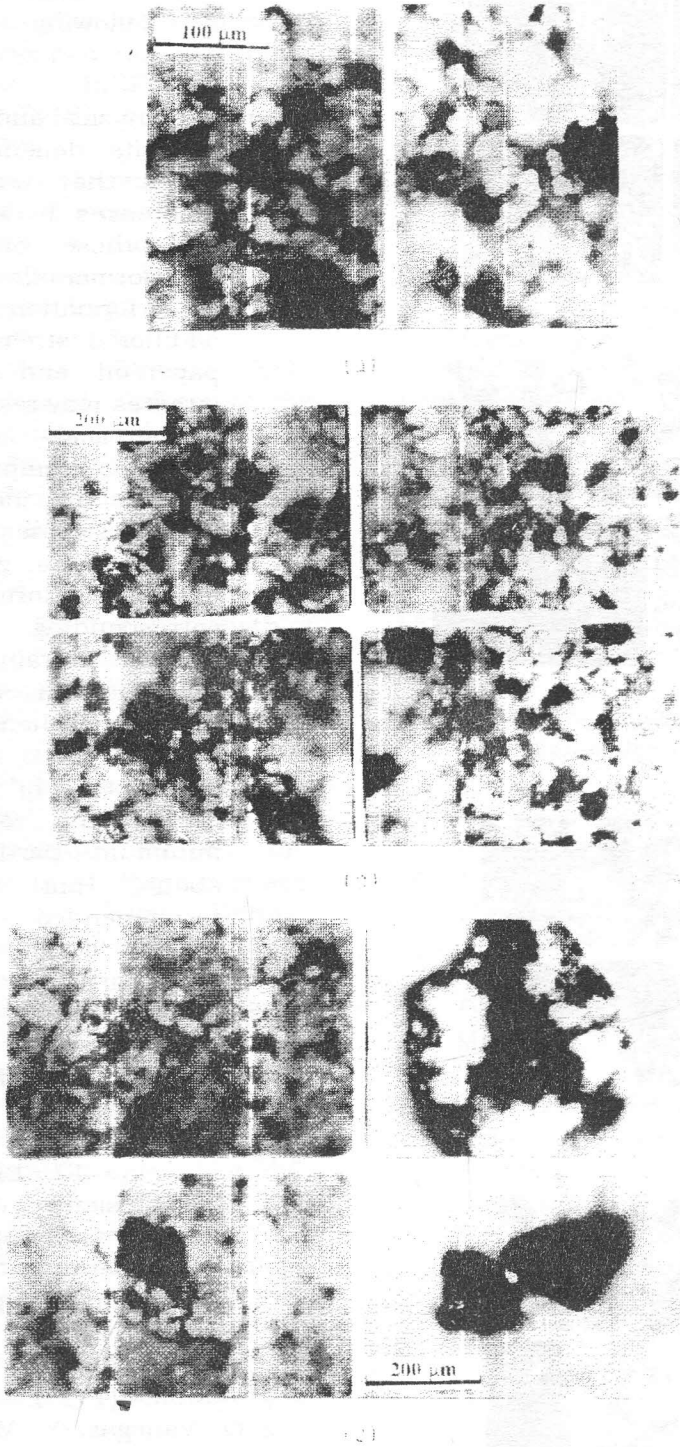
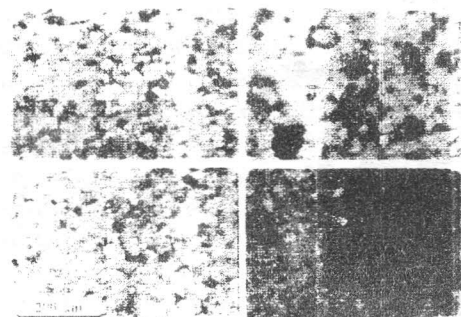
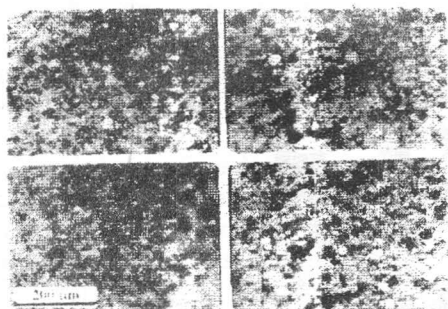


Figure 6 Photomicrographs of deposits 'DA'.



(b)

Figure 7 Photomicrographs of deposits 'DA'.

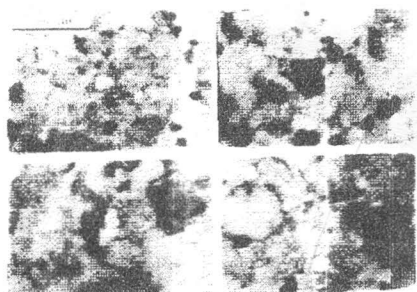
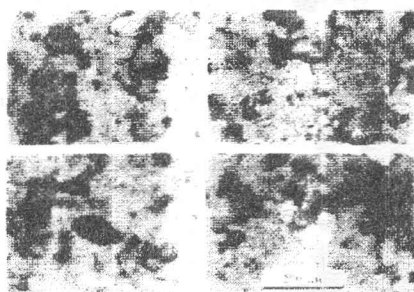


Figure 8 Photomicrographs of deposits 'DC'.

CONCLUSIONS

The following conclusions could be inferred:

1. The physical and chemical properties of deposits depend on the location at which they are formed and distinct differences between deposits properties and those of their corresponding transformer oils are detected.
2. The formation of deposits exerts additional stresses on the transformer paper/oil and solid insulation. These stresses may result from the unreleased water, acids and accumulation of metallic compounds which cause increase in the local electric and thermal stresses.
3. The functional groups of deposits are different from those of the corresponding transformer oil. They contain certain groups depending on the location and the degradation products of the insulation at which they are formed.
4. The types and sizes of deposit solid constituents are determined. The minimum particle size deposited is about $1\mu\text{m}$. If oil flushing is recommended the system should contain a filter that can collect such small particles.
5. The continuous monitoring of deposits is necessary in the design of paper/oil insulation diagnostic and measurement techniques.

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دراسة مكونات الرواسب في نظام عوازل زيتي باستخدام التحليل الطيفي بالأشعة دون الحمراء والفحص الفيروغرافي

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ملخص البحث

في هذا البحث تم دراسة رواسب الزيوت المتكونة في العديد من الخوالات و في أماكن مختلفة من الخول مثل أسطح الملفات و قاع وأسطح خزان الخول وموصلات مغير الخطوة. استخدم في هذه الدراسة التحليل الطيفي بالأشعة دون الحمراء و الفحص الفيروغرافي للرواسب و كذلك تعيين الخواص الفيزيائية و الكيميائية للرواسب وزيت الخول. تبين من الدراسة ما يلي:-

- (١) تتغير مكونات الرواسب تبعاً لتغير المكان المتكونة عليه.
- (٢) أوضحت دراسة الخواص الفيزيائية والكيميائية للزيوت والرواسب أن محتوى المياه و الحمضية الكلية ومحتوى الرماد في الزيوت أقل منه في الرواسب المصاحبة.
- (٣) الاعتماد على خصائص زيت الخول فقط لتقييم نظام العزل الورقي/الزيت غير دقيق في حالة وجود رواسب.
- (٤) استخدام المجموعات الوظيفية الناتجة من التحليل الطيفي بالأشعة دون الحمراء غير كاف لتحديد الإضافات اللازمة لمنع تكون أو اذابة هذه الرواسب.
- (٥) الفحص الفيروغرافي أكد احتواء الرواسب على جزيئات معدنية و أتربة ومكونات أخرى ناتجة من تحلل الزيت و العوازل الصلبة والورقية.
- (٦) تم تحديد حجم الجزيئات الصلبة في مكونات الرواسب وذلك للمساعدة في تحديد مسامية المرشحات اللازمة لتنقية زيوت الشطف في حالة استخدام الشطف كوسيلة لازالة هذه الرواسب.
- (٧) تكون الرواسب يزيد من الاجهادات على العوازل الصلبة و الورقية وزيوت الخوالات وذلك نتيجة لاحتجاز المياه في العوازل الورقية وتركيز الاحماض على أسطحها ووجود المكونات المعدنية التي تزيد من تركيز الاجهادات الكهربائية و الحرارية.
- (٨) نظم التشخيص والمراقبة المستمرة للعوازل في الخوالات يجب أن تأخذ في الاعتبار تكون الرواسب لزيادة الدقة و الفاعلية في التشخيص.