

MAINTENANCE OF INSULATION SYSTEM AND LIFE EXTENSION TECHNIQUES FOR POWER TRANSFORMERS

Vladimir A. Pantic
Elektroistok

Vlastimir Dj. Jovanovic
Minel Transformatori

Dragomir B. Karaulic
Institute of General & Physical Chemistry

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ABSTRACT

The techniques of preventive insulation condition monitoring are shown and the results of quality testing are presented. The decision to use intervention measures is facilitated by using the analysis of these results.

The impact of carbonyl molecules generation on the rate of solid insulation aging, the change of the hydro- phobic character of insulating oils, and the increase of the free electrical charges inside the insulation systems are examined and their functional interdependence is demonstrated.

The employment of a new adsorbent with selective adsorption effect on carbonyls, water, and gases is proposed. The adsorbent is meant to be regenerated, which is of special importance from the point of view of ecology and use on the site.

The benefits of the new adsorbent use are presented, as well as the installation for its use on site while the transformer is in service or out of service in the event that intervention is required.

This paper offers the results of a series of test measurements, together with the analyses of the results attained, and the conclusion reached. Special emphasis is given to the results reached during the work with the new adsorbent as well as the refurbishment of the insulating system while using our new method.

INTRODUCTION

As is well known in the utilization of power transformers, electrical fault and rated currents, the impact of electric and magnetic fields, and overheating, all cause the insulation aging process which can be manifested in the change of oil characteristics and reducing dielectric characteristics of solid insulation. This interferes with the functioning of the transformer system and often causes damage.

The basic problem is in the fact that built-in insulating materials must be chemically and thermally stable when transformers are in use, but unfortunately that is not always the case.

Before being built in, insulation must be maximally dehydrated. This is not easy to accomplish due to the differing adsorption characteristics of cellulose and oil (cellulose is hydrophilic, and oil is hydrophobic).

The problem of sustaining the quality of solid cellulose-based insulation is not solved in any satisfactory manner without the total dehydration of cellulose, while, at the same time, without losing its mechanical and insulating properties. The reason for this statement lies in the chemical instability of cellulose in the processes brought about by operation.

The stabilization of oil to maintain its insulation characteristics has not yet been solved in a satisfactory manner. This problem is especially emphasized by the oxidation process which happens during utilization, and is evidenced by the appearance of lower carbonyl, carboxyl, water, and gases in oil. This is not good for the functioning of a transformer .

According to available data regarding the present state of techniques and technology, the search for a solution of how to maintain and regenerate insulation has developed in two directions:

- Decelerate the degradation process by adding adequate additives-inhibitors;
- Remove the products of oil and cellulose degradation by an adsorption method in order to maintain the initial quality of insulation.

Evaluating these two directions, we see that investigations in both directions are being pursued intensively. This refers especially to materials which might reclaim oil of a transformer in service, without taking it out of operation. Our attention is strictly directed to these latter investigations.

OUR APPROACH TO SOLVING THE INSULATION AGING PROBLEM

When solving the problem of how to maintain the quality of insulation systems, we started from the basic facts, such as:

- The process of the degradation of cellulose and insulating oil during transformer operation cannot be stopped. Consequently, this causes the constant production of degradation products.
- During the process of operation of a transformer system, the inhibitor which is added to oil only slows down, but does not stop, the process of degradation. Once the inhibitor has been permanently spent, the oxidation process is accelerated. The potential of this process is not possible to foresee.
- The water contained in the insulation adsorbed during transformer manufacture, or produced during transformer operation, is divided between the solid insulation and the oil, according to Henry's principle: $C_1/C_2 = K$, where C_1 and C_2 are water concentrations in oil and in solid insulation, and K is the constant. The same ratio applies to all products of degradation. If any C_1 and C_2 values change, it causes equilibrium disturbance, i.e., change of concentration in the second part of the two-part insulation system.
- Products of insulation degradation are dispersed between liquid and solid insulation, regardless of which they appeared in. This is the consequence of the process of diffusion and oil circulation through cellulose. Their presence in oil is the basic cause of reducing the insulating oil dielectric capacity, but by measuring their concentration in oil, the state and condition of transformer insulation can be determined. It should be pointed out that the products of degradation are molecules of clearly polar character, and as such, they can be factors in the development of harmful currents in the electrical and magnetic fields of the transformer insulation system.

These points demonstrate that the regeneration of transformer oil is a complex problem which cannot be solved in anyone step by the existing technology and adsorbents. It is necessary to remove from the oil all the products of degradation, particulate matter, water, and gases in order to preserve the required characteristics of the insulation system and thereby to provide a reliable functioning of the transformer system as a whole.

In the present state of technique and technology, the removal of products of insulation degradation, water and gases, has been done by adsorption process and by vacuum processes independently. Adsorption of carbonyl, carboxyl, and furan type compounds have been done by means of various adsorbents in direct contact with oil. The most frequently used adsorbents for this process are natural materials such as Fuller's earth, active bentonite clay, diatomaceous earth, white bauxite, alumina, zeolite, etc. The results obtained prove that by this technological procedure the problem can be only partly solved. However, the unsolved problem is how to find or synthesize an adsorbent of such characteristics that it can remove most of the products of insulation degradation in one process. Further, how can we enable the development of new, beneficial technical processes in the field of maintenance of transformer insulation system.

The aim of our explorations is the synthesis of the new type of adsorbent, capable of discriminating between macro and medium porous structure, with specific surface and energetic characteristics, which could completely solve the complex problem of regeneration.

CHARACTERISTICS OF THE NEW ADSORBENT

The synthesis of the new adsorbent is the aim of the first stage of our work. Among a number of well-known systems and synthesizing processes, we have looked for the solution in simple and familiar systems in which the process can synthesize adsorbents of the desired characteristics.

The essence of the process is in establishing the concentrated proportions of external characteristics of hydrothermal procedure for producing an active alumino-silicate of maximum adsorption capacity for all products of degradation.

The proposed optimal characteristics which such an adsorbent should have are:

- Mean pore radius in the area of 50-70 Å(K)
- Specific surface area of 180-250 m²/g
- Static adsorption water capacity of a minimum of 22% during a relatively balanced pressure of P/P₀ = 1
- Static adsorption capacity for aliphatic lower carboxyls and carbonyls of 12-16%
- Static adsorption capacity for furanic compounds such as 2-furfuraldehyde of 10-15%.

It should not be forgotten that these processes on the surface of the adsorbent proceed simultaneously and selectively between certain molecular groups in relation to the energetic character of the surface.

Characteristics of the new adsorbent are shown on the Table and in the diagrams which characterize its porous structure.

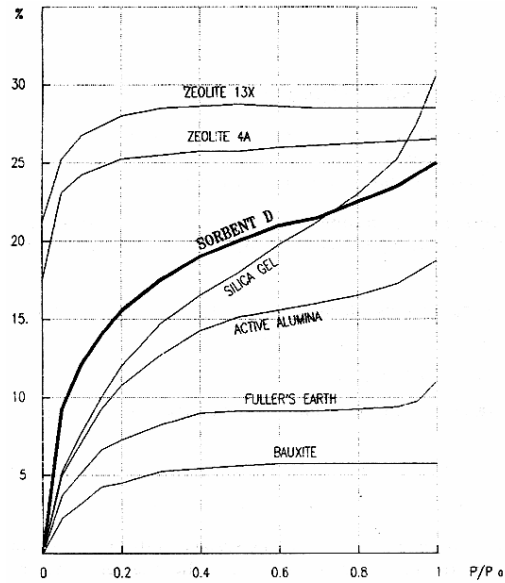
TABLE I Characteristics of the New Adsorbent D

No..	CHARACTERISTIC	UNIT	SUPPOSED VALUE	OBTAINED VALUES
1	Specific surface	m ² / g	150- 250	150- 240
2	Middle pore radius	r- Å	50- 70	50- 80
3	Total pore volume	cm ³	0.35	0.40
4	Static sorption water capacity	%	min. 22	24
5	Static sorption capacity of aliphatic carbonyls	%	12- 16	13.5
6	Static sorption capacity of furan and homologues	%	10- 14	11
7	Form of sorbent	sphere mm	0.5- 1.5	0.5- 1.5

Characteristics of the adsorbent are investigated for their sensitivity to a number of compounds which may appear as oil degradation by-products.

The results obtained are shown as adsorption isotherms, and are compared with the same characteristics of adsorbents of current technology for oil regeneration.

Figure 1 shows water adsorption for the various adsorbents which were tested. As was expected, zeolite adsorption capacity is dominant, especially for lower relative pressures, which is essential for effective removal of low water concentrations from oil.

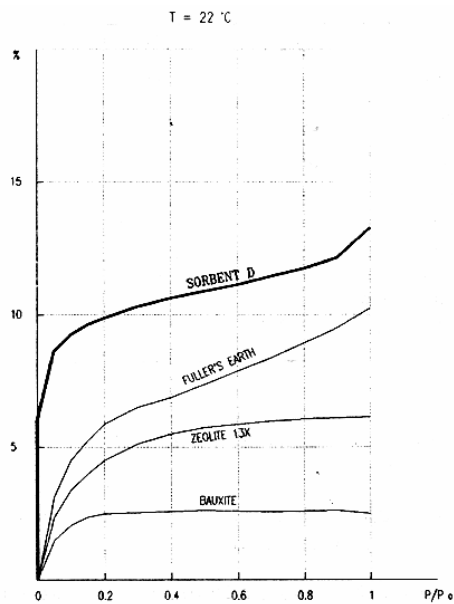


Isotherms of Water Adsorption of Different Adsorbents

FIGURE 1

Our adsorbent, with exception of zeolite, has better adsorption characteristics than the others currently on the market.

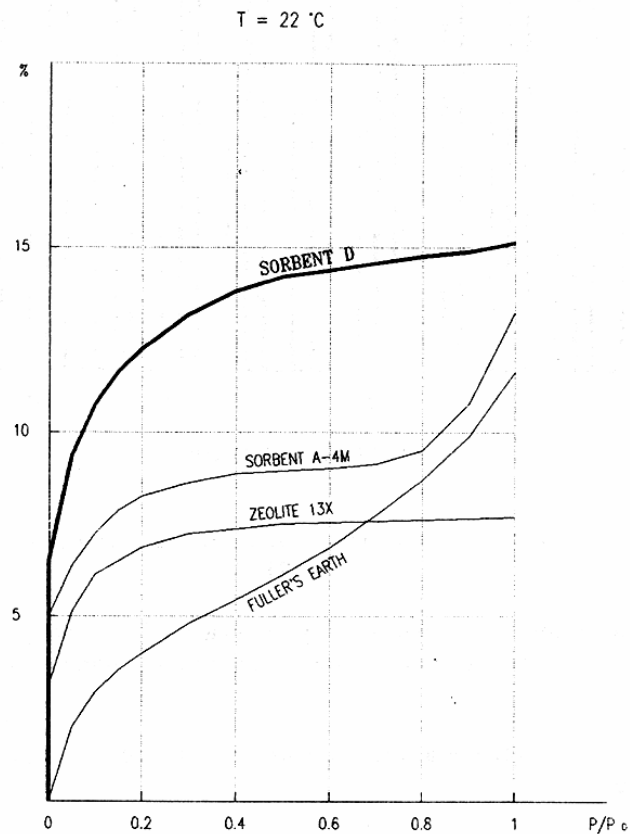
Figure 2 shows isotherms of carbonyl adsorption (ethylaldehyde). Based on the results obtained, adsorbent D shows a greater adsorption capacity than Fuller's earth, zeolite, or bauxite.



Isotherms of Ethylaldehyde (Carbonyl) Adsorbents

FIGURE 2

Figure 3 shows adsorption isotherms for 2-furfuraldehyde on adsorbent D, zeolite 13X, Fuller's earth, and adsorbent A-4M of Russian production.



Isotherms of Adsorption 2-Furfuraldehyde on Different Adsorbents

FIGURE 3

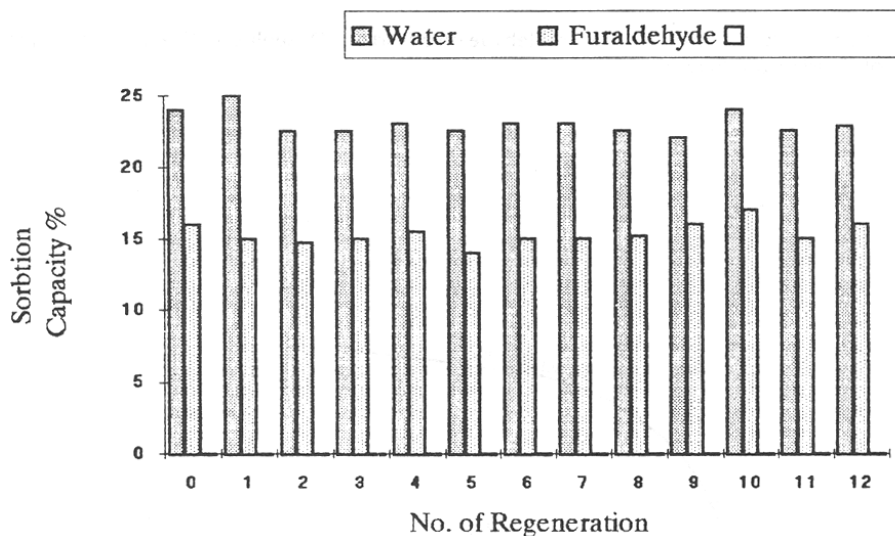
Our general conclusion is that high adsorption activity of adsorbent D to polar compounds of acidic character is attributable to the great number of active sites present on its surface.

Given the analysis of the results obtained, it may be concluded that the new adsorbent has a number of advantages over other adsorbents currently in use. Some important ones are:

- a larger adsorption capacity of at least 30-50% in comparison to currently used adsorbents;
- optimal relation of porous structure and specific surface area;
- favorable kinetic parameters for the process of adsorbent diffusion;
- a high thermal stability and chemical inertness;
- the adsorption process for the examined components indicates that it is a physical adsorption process and therefore the process is completely reversible.

Based on these characteristics, a procedure of adsorbent regeneration has been developed. This procedure entails two main operations: extraction and thermal activation.

In our investigations the process has been repeated many times, and the results obtained are shown in Figure 4.



Change of Adsorption Capacity Depending on the Number of Regenerations

FIGURE 4

In order to define the adsorbent's thermal stability, a review of the changes in the porous structure and specific surface area was used. After ten regenerations, only small changes in these physical characteristics were noticed.

As noted earlier, the ability to regenerate the adsorbent is especially important from an economic and environmental point of view.

DEGRADATION MECHANISM OF INSULATION SYSTEM DURING TRANSFORMER OPERATION

In the course of exploring the synthesis of a new adsorbent and its application in an oil regeneration process, an exploration of the mechanisms of degradation in insulating systems was carried out.

It is not necessary to explain in detail in this paper the mechanisms of insulation degradation, but we assume it is important to place it in its proper context so that we can act effectively in controlling the negative effects of the degradation processes.

We shall quote a few assumptions which were proven by experimentation. These assumptions are essential for deducing certain conclusions (e.g., how to maintain the whole insulation system).

At the beginning of our paper we stressed certain points:

- The insulating system must be considered as a whole.
- The insulating system is composed of two materials: cellulose and oil. Their chemical stability and physical properties are entirely different.

Cellulose is a natural polymer with a great number of functional groups, and therefore is chemically unstable. The concentration of oxygen, which is very important in the oxidation process, is extremely high: oxygen 43%, carbon 51 %, hydrogen 6%. The nature of chemical bonding in the macromolecule is complex with an average energy of 290 kJ/mol. It should be stressed that the bond between monomers in the polymer is considerably lower than this average value.

Insulating oils from a chemical point of view are simpler systems. They are chemically more stable with average bond energy in excess of 420 kJ/mol.

Because of these facts, we proposed the following mechanism:

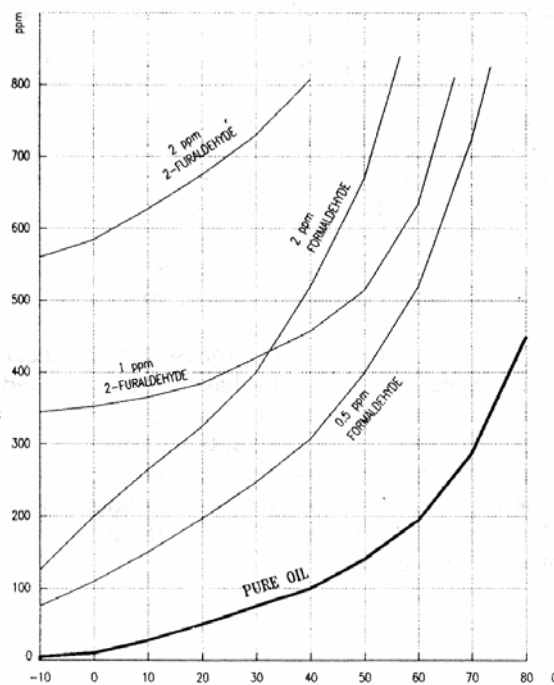
Among the many processes of degradation, one of the first is the process of thermal disassembling of the polymer. This is because the bonds between the monomers are of a low enough energy that it requires a minimal amount of energy to cleave the bond. This process can be qualified and quantified by the determination of the degree of polymerization (SCAN-C15 method), as well as by thermogravimetric (TG) and scanning differential thermal analysis (DTA).

Simultaneously, on the ends of polymer chains, the oxidation process begins and carbonyls form. By diffusion, this process is transferred into the liquid part (oil) of the insulation system where the oxidation process continues to the point where carboxyls appear. The production of carbonyls is manifested by the increase in the neutralization value of the oil.

These two processes are qualitatively identified by infra-red spectroscopy (IR) and quantitatively measured by methods using high performance liquid chromatography (HPLC) and mass spectrometry (MS) through the determination of 2-furfuraldehyde. The neutralization value of the oil is determined by standard methods.

In the process of transferring cellulose degradation products by diffusion into insulating oil, the oil is now subjected to processes of further degradation. The presence of polar molecular compounds or high oxygen content in oil enables many complicated processes to be predicted. We shall mention just a few for which we have evidence: the process of further oxidation causing the formation of carboxyls; decarbonization onto oxide-metal surfaces (catalyzing); production of free radicals; and interaction with other oil molecules or oxidation products, etc.

Irrefutable proof of these processes are seen in the changes in the oil's properties, especially in the loss of insulation characteristics, which consequently leads to the loss of the oil's hydrophobic properties and an increase of its hydrophilic properties. The results of our measurements are shown in Figure 5.



Change of Hydrophobic Oil Property Depending on Temperature and Content of Carbonyls

FIGURE 5

TABLE II
Required Values of Characteristics of Used Insulating Oil
Classified in Groups in Relation to the Degree of Use

Ord. No.	OIL CHARACTERISTICS	I GROUP	II GROUP	III GROUP	IV GROUP
1.	Dielectric Strength kV/ cm				
	up to 110 kV	≥ 140	≥ 140	≥ 120	< 120
	for 110 kV	≥ 180	≥ 180	≥ 160	< 160
	for 220 kV	≥ 220	≥ 200	≥ 200	< 200
	for 400 kV	≥ 220	≥ 200	≥ 200	< 200
2.	Specific Resistance at 90 C, GΩm	≥ 10	≥ 2	≥ 1	< 1
3.	Power Factor at 90 C, x 10 ⁻³	≤ 50	≤ 200	≤ 1000	> 1000
4.	Neutralization Value mg KOH/ g	≤ 0.05	≤ 0.20	≤ 0.30	> 0.30
5.	Sediment in Oil Undissolved and/ or Dissolved	NO	NO	≤ 0.20	> 0.02
6.	Interfacial Tension mN/ m	≥ 25	≥ 20	≥ 15	< 15

Note:

- I - First group: Oil in very good condition
- II - Second group: Oil in good condition
- III - Third group: Oil in usable condition
- IV - Forth group: Oil in useless condition

TABLE III

**Testing Results of Oil Sampling Taken From Elektroistok Transformers
Before and After Revitalization of the Insulation System On-site**

No.	Year of Transf. Produc.	Year of Transf. Testing	Power Factor o/oo	Specif. Resist. MΩm	Neutraliz. Value mgKOH/g	Interf. Tension mN/ m	Oxid. Stabil. h	Sedim. in n-Heptan	Dielec. Strenght kV/ cm
1	2	3	4	5	6	7	8	9	10
1.	1956	1986-P	228.4	1.2	0.31	16.14	-	Yes	-
		1986	16.8	28.5	0.07	31.41	18	No	> 245
		1989	26.7	13.6	0.11	25.42	-	No	> 250
2.	1957	1984-P	448.9	0.6	0.12	20.23	-	Yes	-
		1985	36.4	8.1	0.06	31.86	32	No	192
		1986	75.1	5.7	0.05	28.93	-	No	> 245
		1988	101.6	3.6	0.07	28.59	45	No	132
3.	1957	1985-P	68.1	3.1	0.28	17.09	-	Yes	-
		1985	8.6	40.7	0.05	31.19	35	No	150
		1986	12.7	28.5	0.07	27.86	38	No	103
		1097	16.0	19.0	0.14	27.12	45	No	> 245
		1989	20.1	14.3	0.08	26.97	-	No	132
4.	1958	1984-P	41.4	5.7	0.22	18.97	-	Yes	168
		1984	9.5	54.0	0.04	33.91	20	No	226
		1986	12.4	57.0	0.10	27.40	24	No	> 245
		1989	14.3	24.2	0.10	27.17	-	No	185
5.	1959	1885-P	78.8	2.7	0.21	19.09	-	Yes	-
		1985	9.2	40.7	0.07	32.78	38	No	> 245
		1986	33.8	9.5	0.07	30.16	23	No	235
		1988	39.5	5.7	0.09	27.50	24	No	> 245
6.	1959	1985-P	77.9	2.9	0.12	20.28	-	No	> 245
		1985	27.6	11.4	0.05	31.47	38	No	> 245
		1986	30.7	8.9	0.06	29.78	34	No	> 245
		1988	32.5	8.1	0.07	25.71	40	No	> 245
7.	1959	1983-P	118.4	1.6	0.20	19.43	-	Yes	> 245
		1985	28.9	9.5	0.06	28.72	38	No	> 245
		1986	47.1	6.2	0.07	28.21	38	No	> 245
		1988	49.4	5.0	0.11	25.61	40	Yes	> 245
8.	1959	1983-P	206.7	1.1	0.38	20.50	-	Yes	219
		1985	49.4	7.1	0.06	29.40	22	No	222
		1986	56.5	5.7	0.06	27.44	-	No	> 245
		1988	184.1	4.3	0.11	24.94	30	No	> 245

TABLE III (continued)

No.	Year of Transf. Produc.	Year of Transf. Testing	Power Factor o/oo	Specif. Resist. MΩm	Neutraliz. Value mgKOH/g	Interf. Tension mN/ m	Oxid. Stabil. h	Sedim. in n-Heptan	Dielec. Strenght kV/ cm
1	2	3	4	5	6	7	8	9	10
9.	1960	1983-P	53.2	12.9	0.43	15.58	-	Yes	183
		1985	22.1	14.2	0.11	29.24	29	No	> 245
		1986	32.2	-	0.11	27.37	27	No	> 245
		1987	32.5	10.2	0.14	25.89	36	No	> 245
		1989	38.8	-	0.14	25.08	-	No	202
10.	1964	1986-P	33.9	7.3	0.11	19.48	-	Yes	> 245
		1986	5.5	57.0	0.02	33.50	60	No	> 245
		1986	6.9	> 57.0	0.03	34.62	35	No	> 245
		1987	9.4	35.0	0.02	33.43	-	No	239
11.	1967	1987-P	50.5	4.8	0.19	18.02	-	Yes	> 245
		1988	13.8	28.5	0.06	31.69	120	No	228
		1989	15.5	23.8	0.04	29.64	-	No	> 245
12.	1968	1984-P	105.8	1.3	0.19	16.09	-	Yes	193
		1984	24.5	9.5	0.06	28.06	34	No	> 245
		1985	29.6	8.1	0.06	28.69	-	No	175
		1986	32.2	7.1	0.06	27.70	26	No	> 245
		1988	28.5	7.5	0.07	25.75	-	No	> 245
13.	1968	1886-P	55.4	4.1	0.12	17.51	-	Yes	> 245
		1987	15.8	35.9	0.03	33.00	72	No	> 245
14.	1969	1988-P	87.9	2.7	0.15	16.47	-	Yes	196
		1988	9.2	28.5	0.06	30.87	120	No	> 245
15.	1969	1986-P	58.8	3.7	0.11	20.56	-	Yes	> 245
		1986	15.6	18.9	0.06	28.67	46	No	-
		1987	25.1	9.5	0.05	27.06	-	No	226
		1989	26.2	9.5	0.06	29.80	-	No	> 250
16.	1970	1988-P	69.7	3.0	0.15	20.93	-	Yes	> 245
		1989	19.6	16.8	0.03	38.91	> 120	No	> 250
17.	1970	1987-P	59.2	4.4	0.17	18.16	-	Yes	> 245
		1987	11.9	35.6	0.03	32.41	65	No	> 245
		1989	18.7	18.6	0.04	30.60	-	No	> 250
18.	1971	1986-P	61.8	3.5	0.08	20.09	-	Yes	> 245
		1986	14.6	19.0	0.03	33.06	42	No	> 245
		1988	21.3	13.0	0.03	29.08	70	No	> 245
19.	1971	1985-P	94.4	1.9	0.22	16.96	-	Yes	240
		1986	31.4	8.1	0.07	25.72	44	No	240
		1988	50.8	4.9	0.11	23.60	50	No	> 245

Table III (continued)

No.	Year of Transf. Produc.	Year of Transf. Testing	Power Factor o/oo	Specif. Resist . MΩm	Neutraliz. Value mgKOH/g	Interf. Tension mN/ m	Oxid. Stabil. h	Sedim. in n-Heptan	Dielec. Streight kV/ cm
1	2	3	4	5	6	7	8	9	10
20.	1971	1985-P	40.6	5.6	0.19	22.46	-	Yes	-
		1986	7.1	57.0	0.05	31.13	43	No	> 245
		1987	9.7	35.6	0.06	31.23	42	No	> 245
21.	1971	1985-P	57.5	5.3	0.24	19.02	-	Yes	> 245
		1986	10.5	40.7	0.06	32.66	38	No	-
22.	1973	1984-P	174.9	1.5	0.08	24.30	-	Yes	210
		1984	22.9	14.1	0.03	31.56	56	Yes	> 245
		1985	28.9	11.4	0.03	34.51	-	No	> 245
		1986	29	10.6	0.03		40	No	> 245
		1988	29.5		0.05		-	No	> 245
23.	1974	1987-P	68.3	2.9	0.12	19.33	-	Yes	220
		1989	16.1	35.6	0.02	35.22	90	No	> 250
		1989	19.4	17.6	0.03	34.52	-	No	> 250
24.	1974	1984-P	43.0	4.4	0.19	17.19	-	Yes	> 245
		1986	12.4	23.7	0.03	33.45	70	No	> 245
		1987	13.3	28.5	0.03	31.16	-	No	> 245
		1989	12.7	19.0	0.04	30.68	-	No	> 250

Note:

P- Testing results of insulating oil before revetalization

In conjunction with the insulating oil treatment at the site of a transformer installation, the solid insulation was dried by methods which partly eliminated aging products from that insulation.

Analysis shows the quality of the transformer insulating system after it was processed in the refurbishment treatment. Table III illustrates that the aging process is continuing and that adsorption of the aging products has not been accomplished to the extent that is necessary for our purposes.

For these reasons, we began a search for a new adsorbent of better quality which could provide an improved method of refurbishment of the solid insulation. The result of our research is the new adsorbent which has been discussed, as well as new methods for drying and decontamination of the solid cellulosic insulation. This study deals with refurbishment of insulating oil with a new adsorbent which has many advantages over currently available adsorbents. For comparison or to illustrate this point, we give results of oil treatment with an old adsorbent previously used and with the new one (see Table IV).

TABLE IV
Test Results of Insulating Oil Before and After Use of Old and New Adsorbents

No.	Sample Mark	Power Factor o/oo	Specific Resistance GΩm	Interfacial Tension mN/ m	Neutralization Value mg KOH/g	Sediment
1.	Before Revitalization with 20 % of Old Sorbent	90.2	2.2	15.1	0.08	Yes
2.	After Revitalization	21.0	21.1	30.2	0.03	No
3.	Before Revitalization with New Sorbent with 6 %	116.5	2.1	17.77	0.22	Yes
4.	After Revitalization with New Sorbent with 6 %	2.2	190.0	33.75	0.01	No

Future work will include the use of the new adsorbent in combination with other adsorbents which, from one case to the other, carry out specific functions separating water and gases from the insulating oil. Work on off-line transformers shall be completed by means of a mobile plant where especially polluted insulation systems require complete treatment of the entire system. In practice it has been shown that aging of the solid insulation is greatly decelerated in transformers after a total refurbishment is completed and a stationary apparatus with adsorbents is placed on the transformer. This stationary apparatus continually recirculates the insulating oil thus eliminating aging products, water, and gases. Such apparatus are desirable on new transformers as well (i.e., on transformers whose insulation is in relatively good condition) because it will prevent the degradation processes of the cellulose and insulating oil which are developed by thermal energy influence and by other factors.