EXPERIENCES FROM ON-SITE TRANSFORMER OIL RECLAIMING

ØISTEIN BERG*, KNUT HERDLEVAR
ABB POWER TECHNOLOGY PRODUCTS AS (Norway)

MATS DAHLUND, KJELL RENSTRÖM
ABB POWER TECHOLOGY PRODUCTS AB (Sweden)

ANDREAS DANIELSEN
ABB A/S, DIV. PROCESS INDUSTRIES (Denmark)

UWE THIESS
ABB TRANSFORMATOREN GMBH   (Germany)

1. DEGRADATION OF OIL AND SOLID INSULATION

In the power transformer, both the oil and the solid insulation are subject to aging. The main mechanism for the degradation of the oil is oxidation. Oxidation causes the formation of polar degradation products, with acids and sludge as the final products. Also water is produced in the oxidation process. Ultimately, the production of large amounts of these breakdown products leads to loss of the insulating properties of the oil. Even though the oxidation of oil can be slowed down (by preventing oxygen access, use of high oxidation stability oil, etc.) at some point in time there is a need to either replace the oil or restore its properties.

In the degradation of cellulose several mechanisms are involved. [1, 2] The most important factors to influence the degradation are temperature, moisture and acidity. The latter promotes hydrolysis as well as oxidation.

These two processes, the degradation of oil and the degradation of the solid insulation, have many interactions. The degradation products of one may interfere in the degradation of the other. In some cases they may also to a significant extent accumulate in the other component. Examples of this include low molecular weight acids from the oxidation of the oil that tend to be strongly absorbed by the paper [3], and furanic compounds from the degradation of paper that

are partly dissolved in the oil. The net effect of such phenomena may be very difficult to predict, and the full extent of this interaction and the details of the mechanisms are still far from completely understood. However, there is no doubt that maintaining the oil in good condition also helps prolong the technical life of the solid insulation. In fact, in many cases this may be the most important consideration in decisions on oil maintenance actions.

2. SURVEILLANCE AND MAINTENANCE OF OIL

Normally the status of oil is monitored by the measurement of a number of parameters. These include acidity (or neutralization number), dielectric breakdown voltage, water content, colour, interfacial tension against water, dielectric dissipation factor (or power factor) and inhibitor content, just to mention the most important ones. For each such parameter there is a permissible interval, outside of which some kind of maintenance action should be taken. These intervals vary with type of equipment and voltage class. There is a plethora of such sets of limiting values in the international and national standards that contain guidelines for the surveillance and maintenance of the oil in transformers. The most widely spread standards with international use are ANSI/ IEEE C57.106 and IEC 60422. The present editions are from 1991 and 1989, respectively, and both are under revision at the time of writing.

*Øistein Berg, Power Technology Products AS, Postboks 470, Brakerøya, 3002 Drammen, Norway

Suggested test limits for the new editions are summarized in Tables I and II.

Table I.
IEC test limits for continued use of insulating oil. IEC 60422 was under revision at the time of writing but the values in the table were proposed during the work on the new edition.

parameter	standard	<72,5 kV	72,5-170 kV	>170 kV
Acidity (mg KOH/g)	IEC 62021	0,30	0,15	0,15
Breakdown Voltage (kV/2.5 mm)	IEC 60156	30	40	50
Interfacial Tension (mN/m)	ISO 6295	22	22	22
Dielectric Dissipation Factor	IEC 247	0,200	0,100	0,100

Table II.
Some suggested test limit values for continued use of oil, proposed for the new edition of IEEE C57.106.

parameter	standard	≤69kV	69-230kV	≥230kV
Acidity (mg KOH/g)	ASTM D974-97	0,20	0,15	0,10
Interfacial Tension (mN/m)	ASTM D971-99	25	30	32

Another parameter used to assess the degree of degradation of oil is the "Oxidation Index". The Oxidation Index is obtained by dividing the interfacial tension by the acidity. It has been suggested that oil should be reclaimed or replaced when this values is lower than 300. [4]

3. WHAT IS RECLAIMING?
According to the IEC oil maintenance guide reclaiming is "a process which eliminates, by chemical and adsorbent means, the acidic and colloidal contaminants and products of oil deterioration from the oil, to obtain an oil with many characteristics similar to those of a new product" [5].

Reclaiming should not be confused with re-conditioning, which is "a process which eliminates, by physical means only, solid particles from the oil and decreases water content to an acceptable level" [5].

Several different techniques can be used for reconditioning. Often the process involves filtration and vacuum dehydration of the oil. Thus, in addition to the objectives above there is a reduction of the content of dissolved gases. There may also be small but barely significant effects on parameters such as acidity and dissipation factor. This treatment is often done in order to restore the breakdown voltage of the oil and to lower the water content. By definition, reconditioning is included in the modern reclaiming process.

4. TRADITIONAL RECLAIMING TECHNOLOGY
Reclaiming always involves contacting the oil in some way with a sorbent material, from which it is separated after a suitable treatment period. Fuller´s earth is the most commonly used sorbent and gives excellent results. However, there are many different natural and synthetic materials that can be used for the purpose, with varying results.

There are two main variations. The sorbent can be suspended in the oil while stirring, and subsequently separated from the oil, *e.g.* by filtration. It is also possible to run the oil through percolating columns filled with the sorbent, either by gravity or by pumping the oil.

Both batch-wise treatment and the use of columns can achieve adequate results. However, they both use large amounts of sorbent material, which become contaminated with oil. This makes disposal problematic.

5. MODERN RECLAIMING TECHNOLOGY
The essential elements of the new technology are that relatively small amounts of sorbent are used, and that it is reactivated after each cycle. Typically, the process is run in two alternating modes:

A. The treatment mode, where the oil

1. is drawn from the bottom of the tank,
2. heated,
3. pumped through the sorbent columns,
4. passes a filter and degasser,
5. and finally is returned to the transformer through the expansion vessel

The treatment stage may continue until the efficiency of the sorbent starts to deteriorate, or until it is convenient to switch to the next stage (*e.g.* when running treatment during daytime and reactivation overnight).

B. Reactivation mode
In this stage, the sorbent columns are by-passed, and the oil led directly to the filter-degasser. The sorbent is reactivated, *e.g.* by *in situ* incineration. Meanwhile it is possible to continue to circulate

the oil, in order to lower even further the water content and the amount of dissolved gases.

This process is repeated until the desired oil quality is achieved. Typically, the sorbent can be reactivated several hundred times. This means that the amount of waste per ton of oil treated is very small. Furthermore, this minute quantity of spent sorbent is problem-free from a disposal point of view, since the last reactivation leaves it free from oil.

The final step is to restore the inhibitor content. The appropriate amount is dissolved in a portion of the newly treated oil. This stock solution is introduced in the main oil flow and then circulated until it is well blended. The concentration should be approximately 0.3 %.

6. COMPARISON WITH OIL EXCHANGE

There are several attractive features of reclaiming when compared to exchange of the oil. Although it for safety reasons sometimes may be necessary to shut down the transformer when the equipment is being connected and disconnected, the process can be run when transformers are energized. This can have a large impact on total costs in some cases.

From a technical point of view, the repeated, or rather continuos washing of the solid insulation represents a large advantage. During aging of the oil large amounts of acids, sludge and other degradation products are absorbed by the paper. They can later be redissolved by clean oil. In the case of reclaiming, this happens largely already during the process, in which they are permanently removed shortly after being dissolved from the cellulose. In the case of oil replacement without proper cleaning of the active part (e.g. by "Vapour Phase" processing) these residual degradation products can cause a substantial shortening of the life of the new oil.

7. EFFECTS OF RECLAIMING

During reclaiming of the oil in a transformer, samples are drawn regularly to monitor the progress. Changes of some properties of the oil during tratment are shown in **Fig. 1**.
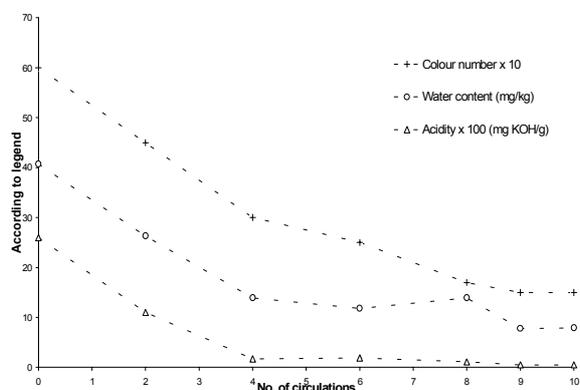

Fig 1. Acidity, colour and water content measured during treatment."No of circulations" is the treated volume

expressed as an equivalent number of total oil volumes of the transformer in question.

Extensive oil analyses are routinely carried out before and immediately after treatment. A follow-up sample is taken after a few months. Data from three mobile units in Scandinavia have been compiled in **Table III**. All transformers are included for which there were results from all three samples available at the time of writing.

We find that all the values measured after reclaiming are better than the IEC 60422 limits for new oil filled in a transformer. This still holds true for the follow-up samples, taken after an average time of 7 months after treatment. Also the suggested test limits for reclaimed oil according to ANSI/IEEE Std 637-1985 are passed.

The small decrease in inhibitor content is likely to be due simply to a dilution effect. During the short time it takes to introduce the inhibitor and circulate it, there is no complete exchange of the oil in the solid insulation.

The results in Table III include transformer oils representing a broad range of degree of degradation. It is reasonable to expect that the results may be less satisfactory for transformers where the oil and solid insulation are severely degraded. Indeed, such trends can be discerned upon close inspection of the data. However, longer treatment times may compensate, to a large degree, for the less favourable starting conditions. Oil from a rectifier transformer of 46 MVA in Germany had strongly acidic oil. Samples of the insulating paper showed very low DP values, indicating severly degraded paper, and thus a high degree of aging of the insulating system in general. However, the results summarized in **Table IV** show that the oil could be successfully restored to good quality after 14 circulations, and that the oil does not deteriorate unusually quickly after treatment.

8. LONG-TERM STABILITY

The long-term stability and oxidation stability of reclaimed oil has been questioned. One reason for this is that the sorbent is believed not to very efficiently remove non-acidic oxidation products. These may act as promoters for oxidation, and cause a more rapid oxidation process than there is for new oil. Another reason, of course, is the possibility of recontamination of acids and sludge from the solid insulation. The latter, however, is likely to be a bigger problem when replacing oil than is the case when reclaiming the old oil. For some transformers, there are data available from several years back. Analysis results from 70 transformers in Norway have been compiled in **Table V**. Transformers for which there are data from at least three years after the treatment have been included. We find that still after more than 3 years there are still only small changes in acidity and colour. The water content of the oil, however, is at the same level as before treatment. Interfacial tension, dissipation factor

and inhibitor content were not measured for these samples.

9. A CLOSER LOOK AT OXIDATION STABILITY

For a number of reclaimed oils, we have done oxidation stability measurements using automated equipment, *viz.* a Metrohm PVC Thermomat. With this type of instrument, it is possible to carry out oxidation induction time determinations in a manner very similar to the method in IEC 1125B. The main difference is that the volatile acidity is measured indirectly by monitoring the conductivity of the water in the absorption vessel [6]. The oxygen flow is also higher, which makes somewhat shorter induction times than are obtained with the IEC standard.

Table VI summarizes the results for all those transformers where Thermomat determinations (as well as full oil analysis results) were available, for all samples up until the first follow-up. We find that in addition to the usual improvement of the common quality indicators, there is also a substantial increase of the induction time. Furthermore, there is no large decrease of the induction time over the first months, when we would expect to see any effects of recontamination of the oil.

We have also tested the Thermomat method with some new oils. These had induction times in the range of 60 hours (standard grade inhibited oils) up to 200 hours (high grade inhibited oils). Considering that there have been some advances in tranformer oil refining technology over the last 30 years, the average value of 111 hours found for reclaimed oils seems quite satisfactory.

10. THE IMPORTANCE OF REINHIBITING

Sometimes the Fuller's earth treatment is carried out without the subsequent addition of inhibitor, *e.g.* in places where inhibited oil is not accepted. However, we cannot recommend this practice, since reinhibiting is an essential part of the treatment.

We have carried out a series of experiments to study the effect on the oxidation stability of the different steps. During the treatment of a transformer in Sweden oil samples were taken before reclaiming, after reclaiming but before inhibitor was added, and finally, after the full treatment including reinhibiting. To a portion of an oil sample taken before reclaiming an addition of inhibitor was made. We thus had the following series of samples:

1. Before any treatment
2. Reinhibiting only
3. Fuller's earth treatment only (no inhibitor added)
4. Fuller's earth treatment and reinhibiting

The oxidation stability of all four samples were tested in the Metrohm PVC Thermomat (see section 9.). The results are shown in Figs. 2-5. It was very clear that reinhibiting on its own had a limited effect (Fig.2 and Fig.3). The oil oxidized at a much higher rate than a new or reclaimed oil.
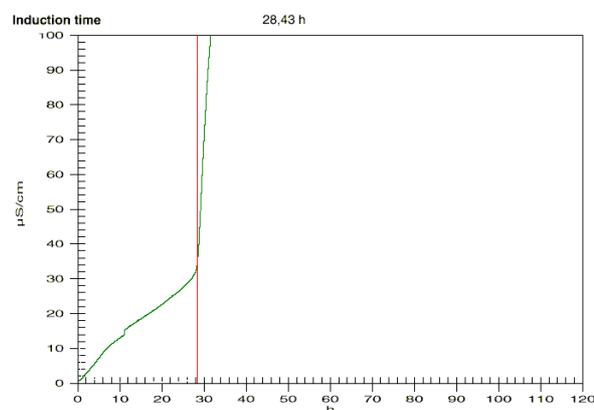

Fig. 2 *Example of oil before reclaiming. The oil had an acidity of 0,08 mg KOH/g and a residual inhibitor content of 0,08%. The induction time (time until on-set of rapid oxidation) was 28 hours.*
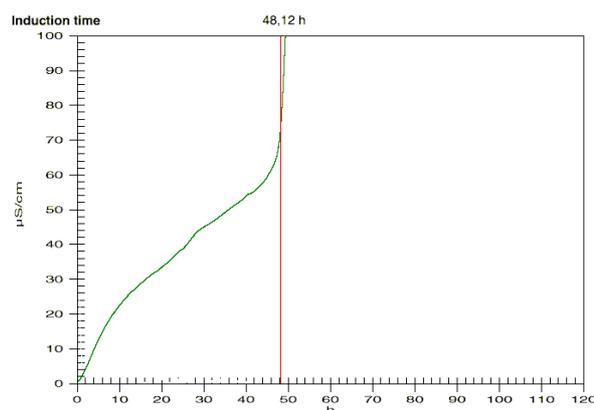
Fig. 3 *Reinhibiting only. The same oil as in Fig.2, with the inhibitor content restored to 0,3%.*
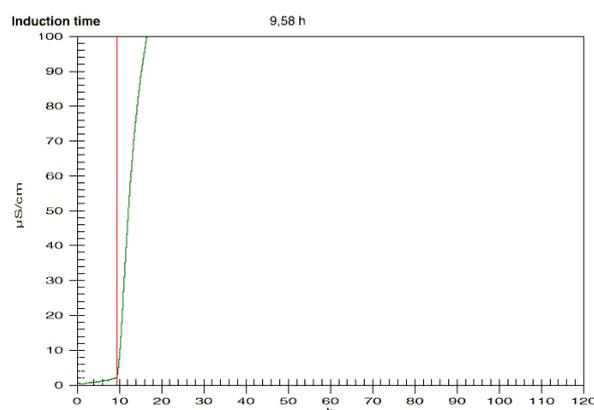
Fig. 4 *Fuller´s earth treatment only. The same oil as in Fig. 1, however after reclaiming, but before the addition of new inhibitor.*
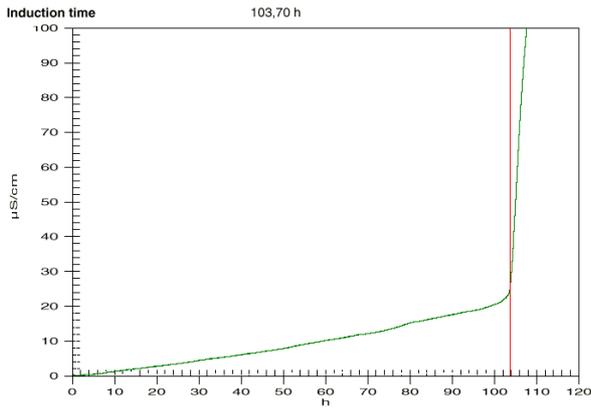
Fig 5. *The same oil after reclaiming and reinhibiting. The induction time is now over 100 hours. The formation rate of acids before the induction time is also lower than it was before treatment.*

Reclaiming without reinhibiting (Fig.4) produced a very clean oil, however with very poor oxidation stability, while the combination of Fuller´s earth treatment and reinhibiting produced an oil with very good oxidation stability (Fig.5). The trends are very clear even though the oil in question was not in very poor condition before reclaiming. It should be pointed out that these results were obtained for an oil that was originally inhibited. For oils that are originally uninhibited the difference is expected to be smaller.

11. CONCLUSIONS
We have found that on-site reclaiming of the oil in energized power transformers restores the oil's properties to very near those of new oil. This holds for all parameters that are routinely measured. The changes in properties during the first years in service after treatment are small.

The oxidation stability of the reclaimed oil is generally very good when the treatment is combined with reinhibiting. There seem to be only very small effects of recontamination from degradation products absorbed in the paper.

The drying effect is moderate and mostly temporary.There is a lowering of water content, which initially is significant. However, it seems to be a temporary effect. For samples taken after 3 years or longer, the water content is generally the same as before treatment.

From an environmental point of view, the advantages compared to oil exchange or traditional reclaiming technology are indisputable. The most important reasons are that oil is not a renewable resource and the new technology causes much less waste of oil and adsorbent than traditional methods.

12. BIBLIOGRAPHY
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5. IEC 60422:1989

6. IEC 601125 (method B)

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Table III. Data from 247 transformer treated in Norway and Sweden. DDF is Dielectric Dissipation Factor, BDV is Breakdown Voltage, IFT is Interfacial Tension, DBPC is content of antioxidant di-t-butylparacresol.

	Acidity (mgKOH/g)	Colour	Water (mg/kg)	BDV (kV/2,5mm)	DDF at 90°C	IFT (mN/m)	DBPC (%)
Before	0,157	4,1	13,7	68	0,0812	23,5	0,040
After	0,009	1,5	6,4	80	0,0033	46,0	0,357
Follow-up	0,014	1,6	8,8	74	0,0063	42,3	0,337
*IEC 60422**	*0,03*	*2,0*	*10-15[++]*	*40-60[++]*	*0,010-0,015[++]*	*35*	*-*
*ANSI/IEEE requirements***	*0,05[+]*	*1,5*	*35-15[++]*	*30[+]*	*-*	*35*	*-*

Table IV. Follow-up of 30 year old rectifier transformer in Germany, with high acidity and severely degraded paper insulation.

Months after treatment	Acidity (mgKOH/g)	Colour	Water (mg/kg)	Breakdown Voltage (kV/2,5mm)	DDF at 90°C	IFT (mN/m)	DBPC (%)
before	0,35	6	55	14	0,110	15	-
0	0,01	2	9	65	0,005	43	0,29
1	0,01	2	8	79	0,008	36	0,29
3	0,01	2	4	71	0,007	41	0,23
5	0,01	2	4	74	0,007	37	0,29
7	0,01	2	2	69	0,008	37	0,27
9	0,01	2	3	61	0,008	39	0,30
15	0,01	2	11	70	0,011	45	0,30

Table V. Data from a period over several years for 70 tranformer treated in Norway. No measurements of DDF, IFT or inhibitor content were avaialble for the 3+ years samples.

	Acidity (mgKOH/g)	Colour	Water (mg/kg)	Breakdown Voltage (kV/2,5mm)	DDF at 90°C	IFT (mN/m)	DBPC (%)
Before	0,162	4,4	11,6	65	0,0919	23,4	0,043
After	0,008	1,9	8,2	73	0,0040	43,0	0,367
1st follow-up*	0,018	1,9	8,7	70	0,0065	39,4	0,370
After 3+ years**	0,028	2,0	11,4	68	-	-	-

*after average 7.7 months
**after average 41 months

Table VI. Data from 16 transformer treated in Sweden. Oxidation induction times have been measured with the Thermomat method.

	Acidity (mgKOH/g)	Colour	Water (mg/kg)	Breakdown Voltage (kV/2,5mm)	DDF at 90°C	IFT (mN/m)	DBPC (%)	Induction time (hours)
Before	0,116	4,0	13,5	77	0,0655	0,037	0,037	21
After	0,009	0,7	3,8	89	0,0031	0,284	0,284	111
Follow-up*	0,009	1,2	6,9	85	0,0079	0,277	0,277	97

*after average 4.5 months