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FAKULTA ELEKTROTECHNICKÁ

KATEDRA TECHNOLOGIÍ A MĚŘENÍ

DIPLOMOVÁ PRÁCE

Life management transformátorů

Bc. Michal Bodanský 2013

ZÁPADOČESKÁ UNIVERZITA V PLZNI
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ZADÁNÍ DIPLOMOVÉ PRÁCE

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Název tématu:	**Life management transformátorů**
Zadávající katedra:	**Katedra technologií a měření**

Zásady pro vypracování:

1. Analyzujte dostupné poznatky o této problematice a připravte systematickou studii současného stavu v řízení životnosti transformátorů.
2. Na základě získaných informací posuďte efektivitu využití metod nebo jejich kombinací pro posouzení životnosti v praxi.
3. Navrhněte rámec metodiky life managementu transformátorů.

Rozsah grafických prací:	**podle doporučení vedoucího**
Rozsah pracovní zprávy:	**30 - 40 stran**
Forma zpracování diplomové práce:	**tištěná/elektronická**
Seznam odborné literatury:	

Student si vhodnou literaturu vyhledá v dostupných pramenech podle doporučení vedoucího práce.

Vedoucí diplomové práce:	**Doc. Ing. Eva Müllerová, Ph.D.** Katedra elektroenergetiky a ekologie

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V Plzni dne 15. října 2012

Abstrakt

Jelikož transformátory jsou jednou z nejdůležitějších a zároveň nejdražších částí distribuční soustavy, je nezbytné zajistit jejich bezporuchový provoz. Efektivním využitím transformátorů se zabývá obor zvaný "Life Management", který se zaměřuje na jejich diagnostiku. Tato diplomová práce je zaměřena převážně na izolační systém transformátoru, neboť selhání izolace způsobí selhání celé jednotky.

První část popisuje, co to je "Life Management" a jeho důležitost v průběhu života transformátoru.

Druhá část je zaměřena na faktory ovlivňující kvalitu izolace olej-papír. Hlavní pozornost je věnována papírové izolaci, jejímu složení a degradaci, která je nevratná. Stupeň degradace je charakterizován "Stupňem polymerizace" (DP). Dále jsou v této části popsány furany, jejich formace a vzájemný vztah s dalšími měřenými veličinami, např. DP, vlhkostí nebo rozpuštěnými plyny. Další důležitou podkapitolou této části je korozivní síra, která je schopná napáchat nemalé škody.

Třetí část se zaobírá měřícími technikami, a to jak on-line tak off-line. Mezi tyto techniky můžeme zařadit analýzu rozpuštěných plynů v oleji (DGA), metody pro detekci korozivní síry a další.

V poslední části je návrh rámce metodiky life management transformátorů.

Klíčová slova

Life management, transformátor, on-line monitoring, stupeň polymerizace, furany, korozivní síra

Abstract

As the transformers are one of the most important and most expensive segments of distributional system, it is necessary to assure their failure-free service. For effective use of transformers there is a branch called "Life Management", which deals with the diagnostic of transformers. This thesis mainly focuses on the insulating system of transformer, because the failure of transformer insulation means the failure of the whole unit.

The first part describes what the "Life Management" is, and its importance during the service life of the transformer.

The second part is focused on factors influencing the quality of oil-paper insulation. There is described mainly paper (cellulose) insulation, its composition and its degradation, which is irreversible. The value of degradation is characterized by the "Degree of Polymerization" (DP). Further, there are described furan derivatives, their formation in oil and its correlation with other measured factors, e.g. DP, moisture or dissolved gasses. There is described a special factor – corrosive sulphur, as well.

The third part concentrates on the measurement techniques, on-line and offline, including Dissolved Gas Analyses (DGA), High Performance Liquid Chromatography (HPLC), methods for detection and mitigation of corrosive sulphur, and others.

The last part describes framework methodology for transformer life management.

Key words

Life management, transformer, on-line monitoring, degree of polymerization, furans, corrosive sulphur

Prohlášení

Prohlašuji, že jsem tuto diplomovou práci vypracoval samostatně s použitím odborné literatury a pramenů uvedených v seznamu, který je součástí této diplomové práce.

Dále prohlašuji, že veškerý software, použitý při řešení této diplomové práce, je legální.

....

podpis

V Plzni dne 6.5.2013 Bc. Michal Bodanský

Poděkování

Velký dík patří vedoucí diplomové práce Doc. Ing. Evě Müllerové, Ph.D., která mi vždy poradila, když jsem potřeboval, a navedla mě na správnou cestu.

Contents

Symbols

A	Factor representative of chemical environment (moisture, acidity, oxygen)
AC	Alternating Current
AN	Acidity Number
ASTM	American Standard Test Method
BTA	Benzotriazole
C	Capacity
CCD	Covered Conductor Deposition Test
D1	Low Energy Discharge
D2	High Energy Discharge
DBDS	Dibenzyl Disulfide
DC	Direct Current
DGA	Dissolved Gas Analysis
DIN	German Institute for Standardization
DP	Degree of Polymerization
DP_t	Remaining DP value after time *t* (200 at the end of life)
DP_0	Initial degree of polymerization (1,000 after drying process)
E	activation energy in kilojoules per mole
F	Farad
FRA	Magnitude Frequency Analysis
g	Gram
GC/MS	Gas Chromatography – Mass Spectrometry
GDGA	Gradient Diluted Gas Analysis
HPLC	High-Performance Liquid Chromatography
HV	High Voltage
Hz	Hertz

IEEE	Institute of Electrical and Electronics Engineers
IEC	International Electro technical Commission
J	Joule
K	Kelvin
LTC	Load Tap Changer
m	Meter
OCB	Oil Cable Box
PCB	Polychlorinated Biphenyls
PD	Partial Discharges
pi	Polarizing index
ppm	Part per Million
PSS	Power Substation Service
QDGA	Quantitative Diluted Gas Analysis
R	The molar gas constant (8,314 J/mole/K)
R_{iz}	Resistance of winding
RVM	Return Voltage Measurment
s	Second
SW	Software
t	Time spent to pass from DP_0 to DP_t (hours)
T	Absolute temperature in Kelvin
$tg\delta$	Dissipation factor of winding
T_r	Time Response
U_p	Break-down Voltage
W	Watt
η	Chain Scissions
Ω	Ohm

Introduction

I have chosen this topic for my thesis because I am interested in power supply and matters of high voltage transformers operating life have a very important role in the distribution of electricity all around the world.

There are many factors influencing the quality of transformer insulation system, some of them are more serious some of them less. However, most of them cause failures during the time. Nowadays, the load of transformers is growing up with the growing consumption of electricity and therefore the diagnostic of this system is required to assure failure-free distribution. To do that, there is a branch called “Life management”.

There are plenty of available scientific articles describing different aspects of ageing or measuring techniques. Nevertheless, almost all of them are focused only on one point. They alternatively compare two of them. The purpose of this thesis is to summarize and describe these aspects influencing operating life of transformers and techniques of their measuring in a complex way.

The thesis is divided into four main parts. The first part deals with life management and its importance nowadays, as the detection of defects in transformer can prevent big damages. The second part describes factors influencing the insulation quality, including not only ageing in transformer insulating system. Furthermore, there are described furans, derivatives determining the statement of paper insulation, and corrosive sulphur, a very reactive compound, contained in almost all transformer fragments. In the third part there are described techniques used for measuring, such a Dissolved gas analyses, High performance liquid chromatography, detection of corrosive sulphur and others. Finally, there is a concept of framework methodology for life management of transformers.

As information sources “IEEE Explore Digital Library” has been used mainly. There are published reliable journal articles, which concentrate on the research of electrical machines and devices. As the universities are usually members of IEEE community, it was possible to have full access to draw from this source and as well as to turn profit all advantages. However, for the corrosive sulphur part, the data have been mainly used from “Doble Engineering”. In this company they do a long term research focused on the influence of sulphur on transformer insulating system.

1 Life management

Consumption of electricity is growing up currently, in consequence of that the load of transformers is also growing up. Population is getting more and more addicted to electricity and power transformers are one of the most important equipment in distributional system. Failure-free distribution is very important, because the damage of transformer causes economic losses in industries, infrastructure and also to the distributor of electricity. These can be millions of euros. For effective usage of transformers there is a branch called “Life Management”, which is important for the responsibility in distribution but also for the decrease of operating costs of owners of transformers and it is also essential because of the increase in transported output. Correct steps in life management lead to the extension of life and also time between maintenance. [1] [2] [3]

Cumulative age of elements and endeavor to decline capital investments for resumption define the targets of life management. The main part is long-term monitoring and identification of problems in the beginning. During its life transformers can break down and there is also natural ageing. There is a tendency to extend the life of the transformer to maximum, and afterwards figure out when to change the old unit for a new one. [1] [2]

It is important to do diagnostic measuring of transformers during all its life in periodical intervals and compare all data. To get the final results it is an advantage to use the initiate unified system for collecting data. It is also important to use diagnostic methods which are necessary for all considerable parameters. [1]

Basic steps of life management:

Analysis of diversification

Valuation of transformers status in accordance with diagnostics

Creation of program for proceeding the life cycle (plan of dynamic loading, plan of service, renovation or change of transformers) [1]

1.1 Diagnostic

Diagnostic is a very important part of maintenance of transformers. Diagnostics examines, if the transformer fulfills the required standard for running.

There are two types of diagnostic: on-line and off-line. [4]

1.1.1 Off-line monitoring

Off-line monitoring is a kind of diagnostic which does the test generating signals. The results are feedbacks of these signals, which designate actual statement of a subject. The diagnostic subject is all the time out of control and the test is done only once or periodically. Its disadvantage is the strictly defined periodicity, which is assigned according to a firmly defined period. On the other hand, these diagnostic methods are well applicable while the transformers are weaned. When the transformers are in operation, we use on-line diagnostic. [1] [4]

1.1.2 On-line monitoring

On-line monitoring evaluates technical aspects of devices by functional diagnostic. It uses operating signals. Some of them are connected constantly and the object is monitored continuously. The advantage of this is the quick reaction to accidental changes.

Monitoring is a preventive and uninterrupted collecting of data and its evaluation. These tests should find weak points of insulation system and specify the degree of degradation. The monitoring system should have the following functions:

Continuous watching of diagnostic values

Security reports when the specific units cross limited values

Instant evaluation of measuring units

In general, measuring under operation is very complicated. It is due to the security during the measurement and also it is necessary to eliminate spurious signals which go along with current functioning. Measuring systems should be faithful, simple and affordable.

A big influence on failure-free statement is the insulating system oil-paper. The main statements are mechanical strain (vibrations), influence of climate, influence of temperature (quick changes), chemical influence (corrosion, oxidation) and electric field (discharges).

Most defects are in the active part (winding and magnetic circuit) and insulating system. The most important parameters are:

Gasses dissolved in oil

Oxygen

Humidity

Temperature

These parameters contribute to the decomposition of oil and cellulose paper. However, the most important of them is temperature.

Detection of breakdowns makes it possible to be prepared for strokes against spreading of this defect and consequential damage of a transformer. [4]

2 Factors influencing the quality of transformer insulation

Transformer insulation consists mainly of oil and paper. There are many factors influencing their compilation, which can lead to a failure. Nevertheless, most of them cause irreversible changes in electrical insulating system. [5]

2.1 Types of ageing

There are several factors causing ageing in transformers. The most influential are listed below.

2.1.1 Thermal ageing

Thermal ageing is influenced by the operating temperature. It includes the progression of physical and chemical changes as an effect of chemical degradation reactions, diffusions, polymerization, depolymerization, etc. There are also included thermo-mechanical effects. These are caused due to thermal contraction or expansion. [5]

2.1.2 Electrical ageing

Electrical ageing is affected by the field strength. This type of ageing includes AC, DC, or impulse. Subsequently it involves:

- The effects of electrolysis;
- The effects of tracking;
- The effects of treeing;
- The effects of raised temperatures originated by high dielectric losses;
- The effects of partial discharges, when the local field strength overreaches the breakdown strength in liquid or gaseous dielectric adjacent to, or involved in, the electrical insulating system;
- The effects of space charges. [5]

2.1.3 Mechanical ageing

Mechanical ageing is affected by the degree of occurrence of repetitive mechanical stresses and the magnitude of non-repetitive stresses. This type of ageing includes subsequent:

- Thermal expansion or contraction causes thermo-mechanical effects;
- Relative movements between equipment components cause abrasive wear;
- Insulation creep or flow under mechanical, electrical or thermal stresses;
- Load of low-level stress cycles cause fatigue failure of insulation elements. [5]

2.2 Ageing in transformer insulating system

The ageing of transformers can be seen mainly at the electro-insulating system, which creates potential barriers, and their failure causes defects. Insulation of high voltage transformers is composed by oil-paper dielectric.

Life is limited mainly by paper insulation of winding, as its strength decreases and the durability is shorter than the durability of other units. Reciprocal relation between oil and paper is very important in the care of the oil. The products, which are produced by the decomposition of oil, are absorbed by paper and on the contrary. This accelerates process of ageing. This is the reason why it is necessary to change the oil before the end of its life, or to regenerate it. Without it the degradation is getting faster and the transformer could be damaged. The vitality of oil is twice or three times shorter then it is of paper. It means that it is very important to do the maintenance. [6]

2.2.1 Winding insulation

2.2.1.1 Introduction

Paper is material made by concretion of fibers. It is composed by vegetable fibers based on cellulose. The most frequently used material is wood, mainly from evergreens; other materials are cotton, hemp and flax. The characteristics give mainly the kind of used stringy materials for its fabrication and manner of manufacturing (melting). Fibrous material for fabrication of paper pulp is made mechanically, chemically or chemic-mechanically. It is necessary to adjust the paper to reach the demanded attributes. Physical properties indicate chemical compilation of raw materials, their morphologic, molecular and over-molecular composition. There are added varieties of polymers, binding materials and extenders, because untreated paper contains only cellulose and it is very absorbent. [2] [7] [8]

2.2.1.2 Cellulose

Cellulose is basic constructive substance of plant tissue. Technical cellulose is also called wood-pulp and it is macromolecular substance, non-reducing polysaccharide composed of monosaccharide – glucose connected with bind. Its molecular formula is $(C_6H_{10}O_5)n$.

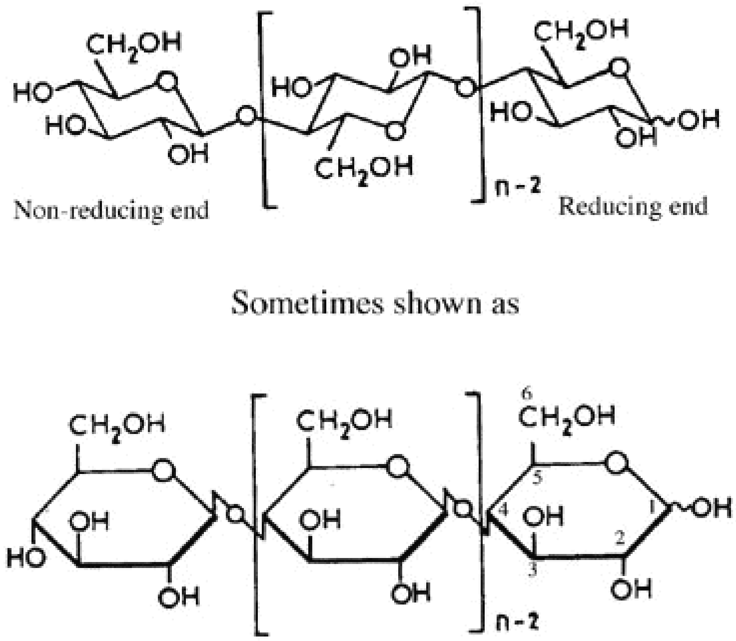


Figure 1: Macromolecule of cellulose [10]

The macromolecule of cellulose (Figure 1) has the shape of long chain where each element is composed of two remains of glucoses. They are connected together by oxygen bridges in alternate positions angled 180° against each other. Each glucose circle includes three hydroxides OH.

Cellulose is the most widespread biopolymer on the Earth. It is a polar tissue which has high dielectric losses and permittivity. It is indissoluble in the water and some chemicals easily absorb moisture. Its molecular weight is 200,000, molar weight is 300,000 – 500,000 g/mole and density is 1,560 kg/m3. [2]

2.2.1.3 Degradation of paper

Ageing of transformer insulation is a function of time (Figure 2), temperature, moisture and oxygen. Temperature has distinctive influence, because the components operate at high temperatures and thermal ageing of cellulose deteriorates its mechanical properties. Mechanical and dielectric properties of solid insulation assign the life of a transformer. For measuring of cellulose condition there exists strong correlation between degree of polymerization (DP) and tensile strength of cellulose. DP value is the main relation between the insulation deterioration and creation of ageing products. [9]

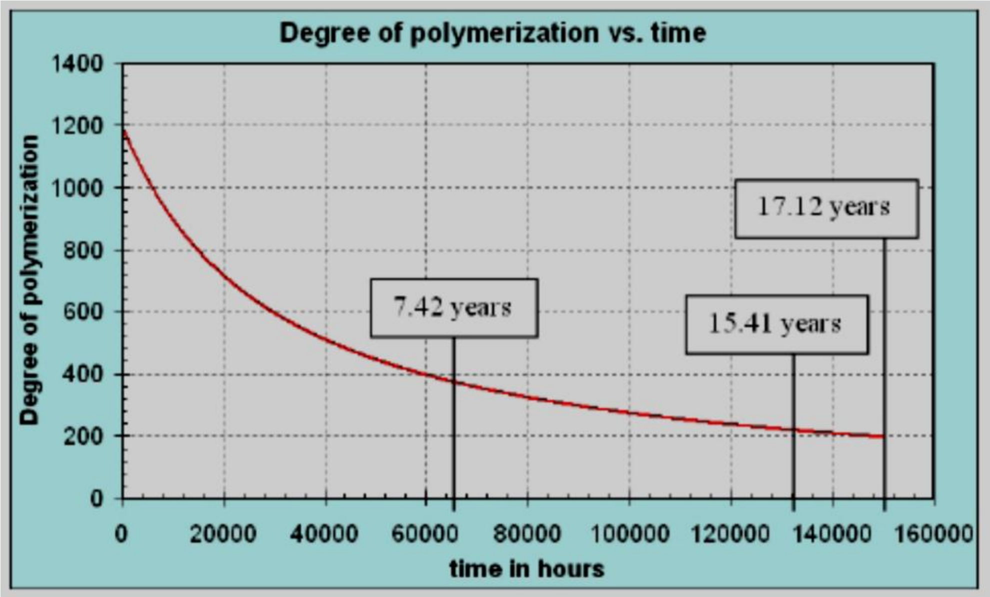


Figure 2: Decrease of degree of polymerization [11]

Decomposition of the cellulose macromolecules indicates the number of anhydroglucouse units in the cellulose chain. The measurement of DP requires removal strips of paper from the transformer and the cellulose sample is not easily assessable. DP is one of the main indicators in ageing process of solid insulation which is made of vegetable cellulose. The basic source of cellulose fiber is wood. Dry wood contains 40 – 50 % of cellulose, 20 – 30 % lignin and 10 – 30 % hemicellulose and polysaccharides. [9]

The viscometric method is used for the measuring of cellulose quality. Average DP based on the viscosity method (DPv) is used for the measurement of the length of the cellulose chain. Average length of new Kraft paper is from 1,000 to 1,500. During the time the paper is getting brittle due to high temperature, moisture and oxygen. DP values decrease to 200 – 250. The Figure 3 shows the effect of temperature and DP on Kraft paper and thermally upgraded paper. Tensile strength of new paper is around 1,200. If the DP value is about 150 – 200, the paper has no mechanical strength and the life of the transformer is at the end. [9]

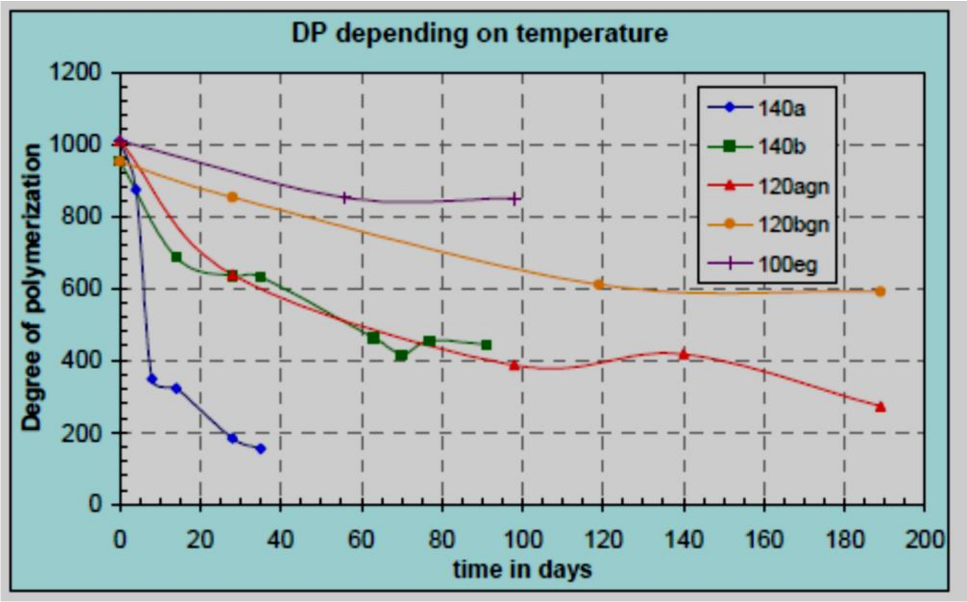


Figure 3: Effect of temperature on the ageing of Kraft paper (140a, 120agn, 100eg) and thermally upgraded paper (140b, 120bgn) [11]

2.2.1.4 General kinetic model for cellulose ageing

Molecular weight and DP of cellulose is reduced during the ageing. It causes that molecular cellulose chains are being cut. *Equation 1* describes the relation between the chain scissions (η) and the measured DP.

$$\eta = \left(DP_0 / DP_t\right) - 1 \tag{1}$$

As the ageing factor we can use the scission of the chain. For example: η = 5, it means that original cellulose chain has been broken in 6 segments. If the starting value is DP_0 = 1,200, this gives DP_t = 200. In general, new paper has a DP of approximately 1,000 – 1,200 and as the “end of life” of the paper is considered value of DP about 200 – 300.

Ekenstam showed the direct relationship of reciprocal DP with time. He combined temperature dependance with Arrhenius *Equation 2*.

$$\frac{1}{DP_t} - \frac{1}{DP_0} = A \times e^{\frac{-E}{R \times (T+273)}} \times t \tag{2}$$

DP_t remaining DP value after time *t* (200 at the end of life)

DP_0 initial degree of polymerization (1,000 after drying process)

A factor representative of chemical environment (moisture, acidity, oxygen)

R the molar gas constant (8,314 J/mole/K)

T absolute temperature in Kelvin

E activation energy in kilojoules per mole

t time spent to pass from DP_0 to DP_t (hours)

DP_t as a function of A, E, T, t and DP_0 in *Equation 3*.

$$DP_t = \frac{1}{\left(A \times e^{\frac{-E}{R\times(T+273)}} \times t\right) + \frac{1}{DP_0}} \qquad (3)$$

The rate of degradation is affected by the operating temperature of the transformer. If the temperature changes by 2°C to 25°C, the ageing value of most chemical reaction rates doubles. Everything depends on the activation energy which is from 85kJ/mole to 120kJ/mole. According to Emsley, the average activation energy is 111kJ/mole (±6 kJ/mole). [11]

2.2.2 Oil insulation

Minerals oils are usually used in the transformers as oil insulation. They are made by refining a fraction of the hydrocarbons gathered throughout the distillation of petroleum crude stock. Mineral oils are composed of a complex of basic hydrocarbon liquids, such as paraffin (40% – 60%), naphthene (30% – 50%), aromatic (5% – 20%), and olefin (around 1%). Fundamental physical and chemical properties of HV transformer insulating oils are summed up in Table 1. Mineral oils are good insulating and cooling agents because of their low viscosity and good ageing behavior. However, their electrical and dielectric quality is strongly dependent on temperature and moisture content. The main advantages are their wide availability and low cost. They have also relatively low permittivity. Nevertheless, they have low flash point and they are slightly toxic. [12]

General physical properties		Fire properties	
Density, 23°C [kg/m^3]	856	Flash point [°C]	150 -> 175
Density, 90°C [kg/m^3]	810	Flame point [°C]	130 -> 135
Pour point [°C]	-40	Combination heat [10^{-3}kJ/kg]	46
Toxicity	Slightly toxic	Self-ignition [°C]	330
Biodegradability	High		
Water solubility, 20°C [ppm]	45		
Water solubility, 100°C [ppm]	650		
Heat transfer		**Electrical properties (at 23°C)**	
Cinematic viscosity, 20°C [mm^2/s]	16	Breakdown strength (AC)U_{VDE} [kV]	>60
Cinematic viscosity, 100°C [mm^2/s]	2.3	Relative permittivity ε_r' (25°C, 50 Hz)	2.2
Heat capacity, 20°C [W/(mK)]	0.135	Dissipation factor, tanδ (90°C, 50 Hz)	>10 x 10-4
Heat capacity, (0°C [W/(mK)]	0.125	Volume resistivity [Ω.cm]	>100 x 10-12
Specific heat, 20°C [kJ/kg.K]	1.85		

Table 1: Physical and electrical properties of HV transformer mineral oils [12]

2.3 Furans

As it is very complicated to get a paper insulation sample from the transformer in service, it is necessary to have another relevant method for assessment of cellulose degradation. This degradation is measured by indirect methods. It means measuring of products dissolved in transformer oil. The samples of oil can be easily collected from servicing transformers. There were many laboratory experiments which show the furan derivatives as a reliable sign of ageing process in a transformer. [14][13]

The content of furans is measured by high-performance liquid chromatography (HPLC) or gas chromatography – mass spectrometry (GC/MS). The concentration of all furan derivatives (Table 2) is detected with them. [13]

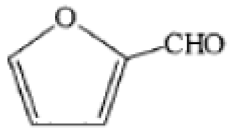
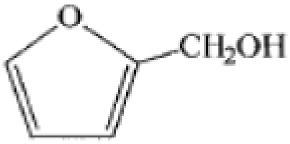
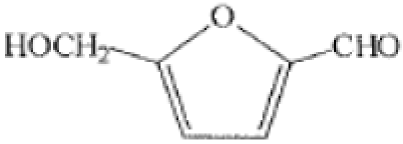
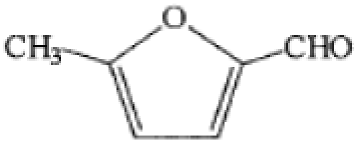
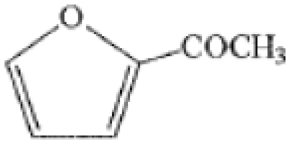
	2-Furfural (2-FAL)
	2-Furfurol (2-FOL)
	5-Hydroxy methyl-2-furfural (5-HMF)
	5-Methyl-2-furfural (5-MEF)
	2-Acetylfuran (2-ACF)

Table 2: Furan compounds detectable in transformer oil [13]

HPLC and GC/MS are methods which require an expert person to do the test and explicate its results. Furthermore, the equipment for measuring is relatively expensive and it takes a long time to get the results. [15]

2.3.1 Mechanism of furan formation

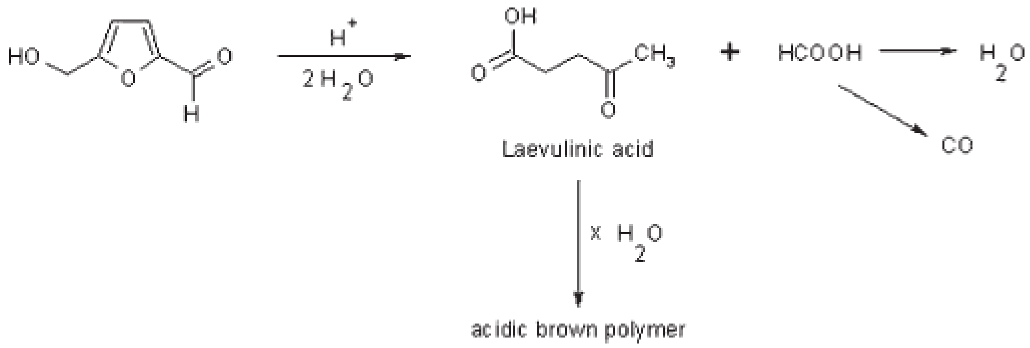
There are two mechanisms of furan formation:

The first one is the pyrolytic one, when temperatures are >130°C. All furan derivatives are composed, not only 2-FAL. Pyrolysis is the most significant mechanism for furan composition in case of anomalous hot spot in a transformer.

Another mechanism is an oxidative hydrolysis of cellulose which forms monomeric hexoses isomerizing in pentoses. This is the most significant source of 2-FAL when the transformer is at normal service temperatures (*Equation 4*).

$$\text{Cellulose} \xrightarrow{\text{Hydrolysis}} \text{Hexose(Glucose)} \xrightarrow[\substack{-\text{CO} \\ -\text{CO}_2}]{\text{Oxidation}} \text{Pentose} \longrightarrow 2-\text{FAL} \qquad (4)$$

If the conditions are acid, glucose forms 2-HMF (2- hydroxymethylfurfural). Furthermore it can be demoted to formic acid and water, or to acidic polymers (sludge). Carbon oxides are afterwards formed from the formic acid (*Equation 5*).



(5)

The products of oxidative hydrolysis are mainly acids, thus a solid insulation can by destroyed by them even at ambient temperature. [14]

2.3.2 Furans vs. DP

During the measuring a correlation between paper DP and furan level was found out. Expansion of furan concentration in transformer oil is consistent with a decline in the tensile strength and the DP of the insulation paper. De Pablo published relation (*Equation 6*) between furfural and DP construct on viscosity (DP_V).

$$DP_V = \frac{7{,}100}{8.88 + 2FAL} \qquad (6)$$

2FAL is the 2-furfural concentration in mg/kg of oil. [15]

There was done research in formation of furan products in a transformer. The results also show the correlation between DP and furans. The decline of DP at 140°C in comparison with the rise of furfural concentration in the oil is shown in Figure 4. Using the kinetic model evolved by Emsley and Heywood the solid line from DP data was derived. Initial rising in furfural concentration is shown in pasted diagram. In Figure 5 we can see a graph proving empirical relationship of the logarithm of the concentration of 2-furfural to the DP of paper in the temperature range 120 – 160°C. [16]

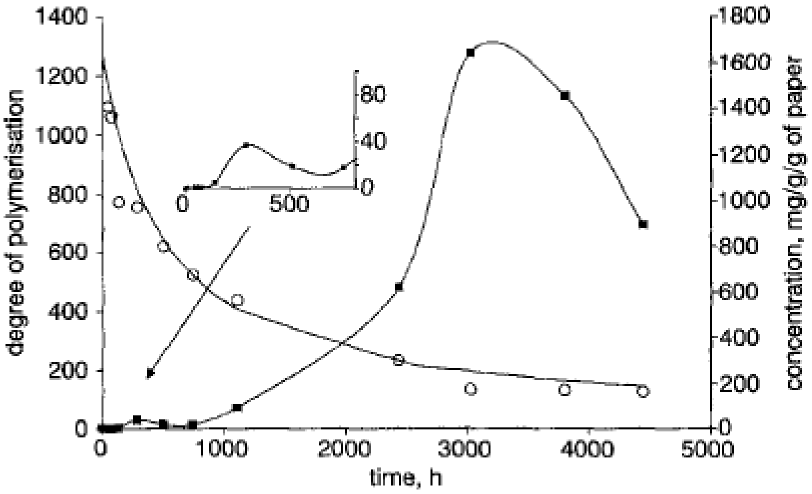


Figure 4: Comparison of change of DP of paper with increase in concentration of 2-furfural in oil during ageing of Kraft paper in oil at 140°C (○ DP, ■ 2-furfural) [16]

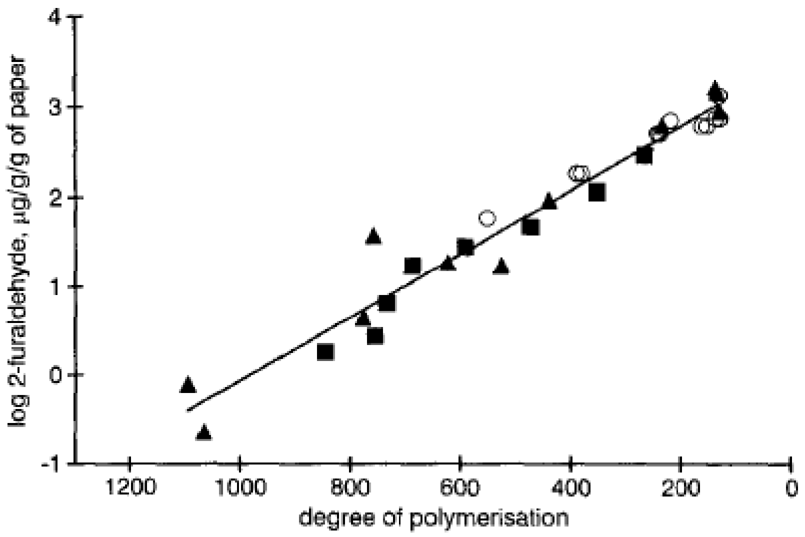


Figure 5: Correlation of DP to LN (2-furfural concentration) for Kraft paper aged in oil at 120 – 160°C. (■ 120°C, ▲ 140°C, ○ 160°C) [16]

Below DP 400 the furfural level starts to rise up considerably as it reaches the value of DP 200, where the paper loses its mechanical strength and becomes inclinable to damage. [16]

Correlation between DP and 2-furfural respecting health conditions of insulation paper, is shown in Table 3.

2-FAL, ppm	DP value	Significance
0 – 0.1	1,200 – 700	Healthy insulation
0.1 – 1.0	700 – 450	Moderate deterioration
1 – 10	450 – 250	Extensive deterioration
>10	>250	End of life criteria

Table 3: DP and 2-furfuraldehyde correlation [15]

2.3.3 Furans vs. Gasses

In the study of correlation furans and gas dissolved in a transformer more than 201 records from different operating transformers were collected. At the same time there were measured furan concentrations with HPLC and also other information such as voltage rating, CO and CO_2 content, capacity, etc. Therefore a database for ageing estimation could be established. The comparison of furfural concentration and gases CO and CO_2 is shown in Table 4. [17]

Statistic parameters	Furfural (mg/L)	CO (10-6)	CO2 (10-6)
Minimum	0.0	36.0	100.0
Maximum	2.76	2,879.0	35,000.0
Mean	0.19	716.29	7,349.12
Std. Deviation	0.38	522.64	6,968.36
Variance	0.14	27,314.80	4.9E+07

Table 4: Comparison of furfural content, CO and CO_2 [17]

Dissolved gas in oil is a well known indicator of faults in oil-loaded transformers. Thus for more complex description of health conditions of transformer integration of dissolved gasses and furfural measuring could be used. Nevertheless, up to now no indicative relationship has been detected. Partial correlation analysis and correlation analysis have been done. Their results are presented in Table 5 and Table 6; significance more than 0.05 indicates free correlation between them. [17]

Content of DGA	Furfural concentration	
	Correlation coefficient	**Signification of test**
CO	0.102	0.149
CO_2	0.308	<0.001
$CO + CO_2$	0.377	<0.001
CO_2/CO	0.231	0.001

Table 5: Correlation analysis between furfural and DGA [17]

Control variables	Gas type	Furfural concentration	
		Correlation coefficient	**Significance of test**
CO2, C0+CO_2, CO_2/CO	CO	0.102	0.149
CO, CO+CO_2, CO_2/CO	CO_2	0.384	0.000
CO, CO_2, CO/CO_2	$CO + CO_2$	0.377	0.000
CO, CO_2, CO + CO_2	CO_2/CO	0.231	0.001

Table 6: Statistic parameters versus different gasses [17]

There are theories that dissimilarity in the mechanism of production may lead to the free correlation between dissolved inflammable gases and the furfural concentration. Still, there is relation of furfural and content of oil-dissolved CO_2, $CO + CO_2$ and CO_2/CO.

CO and CO_2 are also products of cellulose degradation as furfural. Therefore, the information of their content can be used for more accurate judgments of the solid insulation. However, IEEE recommends the utilization of ratio of CO_2/CO, because the content of CO_2 is quite spread. [17]

2.3.4 Furans vs. Moisture

In Siemens Transformer Factory in Germany the correlation between furans and moisture content in the solid insulation was studied. Dependence of 2-FAL and DP with the influence of the initial moisture content is shown in Figure 6. [14]

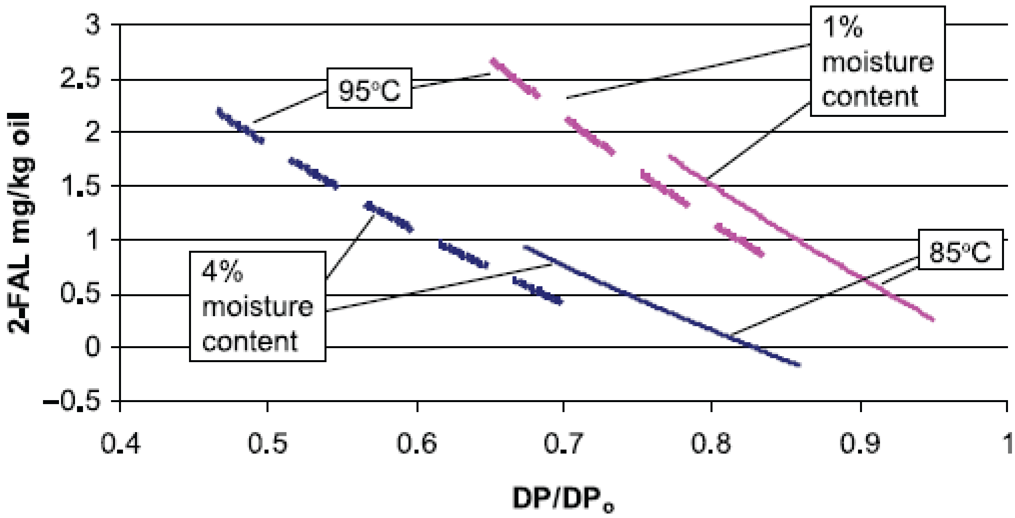


Figure 6: Variation in 2-FAL with DP at different temperatures and initial moisture contents. [14]

Curves are shown for 85°C (thick line) and 95°C (dashed line) for different initial moisture contents in the pressboard. (DP_0 is the DP value of pressboard prior to ageing.) [14]

Laboratory experiment shows that 1ppm of 2-FAL amounts to a DP of 800 at 95°C or to a DP of 900 at 85°C for dry cellulose (content of moisture is less than 1%). If the moisture content is about 4%, 1 ppm of 2-FAL amounts to a DP of 600 at 95°C and a DP of 700 at 85°C. These results indicate dependence of furan concentration on moisture content and the temperature of the oil. The influence of the moisture content on furan formation is higher than the difference between temperatures of range from 75°C to 85°C.

Relation between 2-FAL and DP/DP_0 at 85°C and 95°C allows the plotting of curves that are parallel and shifted to another at moisture content in the solid insulation up to 4%. The curves at the temperature 75°C and moisture content up to 4% were almost identical to those at 85°C and moisture content less than 1%. At the initial moisture content of 12% the behavior of 2-FAL was extraordinary. At the lowest temperature 75°C, there was the highest quantity of 2-FAL.

The behavior of the furan/DP curves at different moisture contents and temperatures is very similar. They are separated and parallel to each other. The influence of moisture content on furan concentration looks more considerable than the influence of temperature.

There were experiments at moisture contents up to 10% and temperature 75°C. During them some extraordinary behavior has been noticed. It is because of almost the same moisture content in comparison with the inception. Moreover, furans are hydrophilic compounds, thus with a higher moisture content in the oil, their dissolvability rises up. [14]

In the temperatures between 75°C and 95°C, the temperature is not the most expressive factor for furan progression and reduction of solid insulation, it is moisture content. Therefore, furans can be used as indirect indicators for moisture content in solid insulation. The variation in the 2-FAL with DP at various average moisture content grades in the solid insulation is shown in Figure 7. [14]

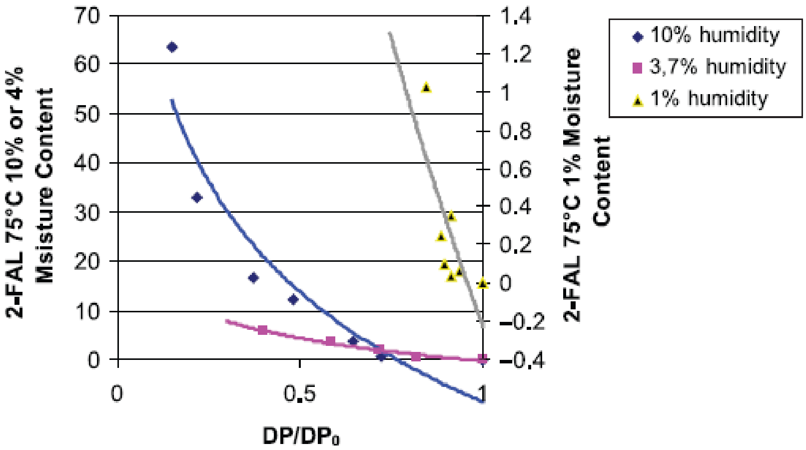


Figure 7: Variation in the 2-FAL (mg/kg) in oil with DP of pressboard with average moisture contents of 10, 3.7, and <1% at 75°C. (DP_0 is the DP value of pressboard prior to ageing.) [14]

2.4 Corrosive sulphur

2.4.1 Introduction

The effect of corrosive sulphur in transformer system can be considerable. The degree of the corrosion damage caused by sulfur can be so critical that it can cause the breakdown of the apparatus. Already in 1948, F. M. Clark and E. L. Raab published a report about method development. It is known now as ASTM Committee D 27, recently ASTM Method D 1275 became. The fact is that transformer construction contains many materials including sulphur. Those are copper, paper insulation, oil and gasket. Nevertheless, not all sulphur is regarded as corrosive. Transformers operate at higher temperatures. This can increase the presence of corrosive sulphur condition or transform stable compounds into reactive ones that will cause damage. [18]

There have been a number of failures of very large power transformers dedicated with corrosive sulphur in electrical insulating mineral oils. There have been only about 100 units which failed. However, the losses have been extensive. Problems have been notified from many countries. The oils passed internationally respected specifications at the time for the corrosive sulphur test involving ASTM D 1275A or DIN 51353. Through that the failures occurred. [19] [20]

2.4.2 Presence of sulphur in mineral oil

There are different kinds of sulphur compounds in refined transformer oil. Nevertheless, not all of them are thought to be corrosive or reactive. Elemental sulphur and sulphur compounds in concentrations up to 20% include crude oil used to produce transformer oil. There are five elemental groups of sulphur and sulphur compounds occurring in crude oil.

Group	**Chemical formula**	**Reactivity**
Elemental (Free) Sulphur	S	Very Reactive
Mercaptans (thiols)	R-SH	Very Reactive
Sulfides (thio-ethers)	$R\text{-}S\text{-}R_1$	Reactive
Disulfides	R-S•S-R	Stable
Thiophenes	Five-membered ring containing sulphur	Very Stable

R = paraffin with straight or branched chain hydrocarbon or cyclic hydrocarbon

Table 7: Sulphur and Suplhur Compounds Found in Crude Oil [18]

As shown in the Table 7, elemental sulphur and mercaptans containing sulphur are very reactive. Reactive sulphur is primarily in the form of organic sulphur compounds like R-SH, where the sulpuhr is joined at the end of an organic molecule. Sulfides are the following ones. Then disulfides, which are formed with more complex molecule makes the sulphur compound more stable and less reactive, like R-S•S-R. Last group, thiophenes, is the most stable of these sulphur compounds. [18]

In reality some sulphur compounds can aid in the oxidation stability of the transformer oil. They can also behave as metal passivators and deactivators which reduce the catalytic effect on oil oxidation in transformers. The object of refining process is to take away or convert plenty of the corrosive and reactive sulphur species to more stabilized compounds such as thiophenes in an unsaturated ring and disulfides in a saturated form. Atmospheric distillation at various temperatures, vacuum distillation, catalytic reaction and hydro-treating and hydro-generation, these are the steps in the refining procedure. Regrettably, the refining process is not always completely successful. Unfinished refining may leave slight quantities of mercaptans behind or the hydrogenation procedure may produce elemental sulphur contrary to hydrogen sulfide. There is still some sulphur left in the new oil after the refining. Nevertheless, it is expected to be from 0.02% to 1%. [18]

Anyway, oil is not the only object that includes sulphur. Sulphur compounds are also in the gaskets, some water based glues, copper and paper insulation used for making transformers. There is also the possibility that sulphur can get into the transformer accidentally, e.g., by using incompatible hoses. [18]

2.4.3 Corrosive and reactive sulphur

All organic sulphur compounds react with mercury to form sulfide, such as mercaptans. This is the definition of corrosive sulphur species. Then there is elemental sulphur which is very reactive and reacts to form corrosive acids. Only low elemental sulphur grade (low ppm range) can cause a corrosive condition. Therefore only elemental sulphur was defined as corrosive sulphur while other organo-sulphur compounds causing corrosive condition are called reactive sulphur. [18]

Copper and other metals react with corrosive and reactive sulphur. The resistance of copper to a sulphur attack is very week. The fact that elemental sulphur can react with copper without influence of heat is even more problematic. In sealed, gas blanketed and sealed conservator transformers, where the surrounding is with the lack of oxygen, corrosive and reactive sulphur species join with copper, aluminum and other metals to form copper or cuprous sulfide (Cu_2S), aluminum sulfide (Al_2S_3) and other inorganic sulfides. Copper sulfide can be confused with carbon, because of its black, gray, blue, green or violet colors. Aluminum sulfide can become very gray in the presence of oxygen and water. Normally it is yellowish-gray material. [18]

Oxygen surrounding occurs in sealed transformers that have a substantial leak, free breathing transformers, free breathing conservator transformers and another free breathing apparatus such as OCBs and LTCs. Different kinds of compounds are composed from the reaction of sulphur with metals. Copper itself can contain some oxygen. The copper used for windings has a minimum copper purity demanded 99.90% and this material is not reckoned as oxygen free (<5 ppm). Various grades of copper can contain higher quantity of oxygen, which can react with sulphur. Thus, manufacturers of the transformers must be careful during the selection of the right grade of material for construction. Reactions including oxygen, sulphur, aluminum, copper or other metals can produce copper or copper sulfate ($CuSO_4$), cuprous sulfite (Cu_2SO_3), aluminum sulfate [$Al_2(SO_4)_3$], and other inorganic sulfates. [18]

There is also the question if noncorrosive sulphur species can be changed to corrosive and reactive species in a transformer. Practically it is possible. Noncorrosive sulphur can turn out to be corrosive after the exposure of increased temperatures on hot metal surface and hence produce metal sulfides. The metal surfaces would corrode after this attack and even worse, the corrosion substance could separate and become nuclei for discharge and gas inception. It is not adequate to cause large damage for oils that pass the corrosive sulphur test and thus contain low sulphur contents. [18]

2.4.4 Transformer failure mechanism involving corrosive sulphur

There are two failure mechanisms that can appear independently or accord in each other. Copper or silver is attacked by corrosive sulphur and this will create copper or silver sulfide on the top of the metal. Sulphur builds up layers and from them metal sulfide fragments can begin to drop off the surface and perhaps into insulation in high stress localities where a dielectric failing can happen. At Figure 8 there is shown a widely contaminated copper strip on the left. On the right side, there is copper strip at a further stadium. The copper sulfide material initiates to flake off the copper. The glossy under the surfaces of the flakes is copper that has fallen out the strip with the copper sulfide. [20]

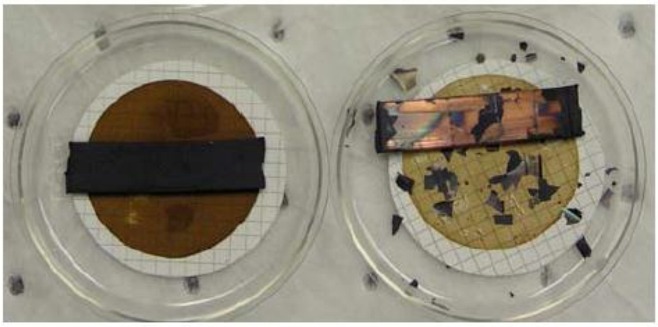


Figure 8: Copper Sulfide Flaking [20]

At Figure 9 there is a scanning electron micrograph of a copper cover that is going to be attacked by corrosive sulphur.

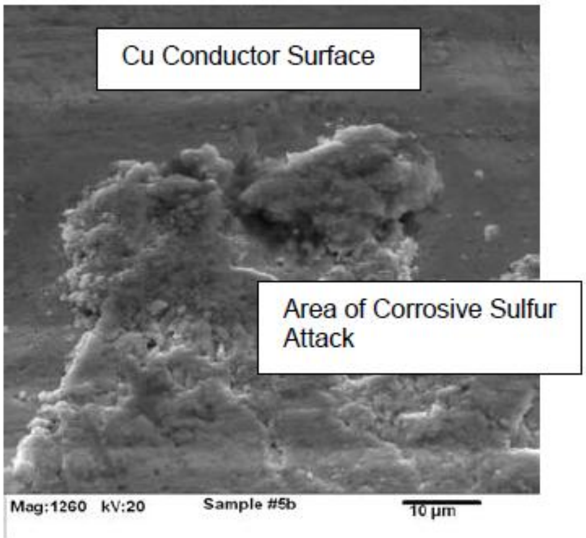


Figure 9: Magnified View of Corrosive Sulfur Attack on Copper [20]

If we look closely at the copper sulfide flakes, the copper sulfide (Cu_2S) layer is thickening. It is caused by forming copper sulfide on the surface. This accumulative process remains until Cu_2S flake divorce from the surface and drop into the bulk oil or to insulating materials. Thickness of these divorced flakes can be tiny as 1 – 2 microns, but flakes up to 8 microns thick have been matched. [20]

There were numbers of failures which are connected with the second mechanism. In the course of time, especially at warmer temperatures, corrosive sulphur in the oil or sulphur compounds turn to corrosive reaction with copper, silver and other reactive metals to create metal sulfides. The sulfides are mainly formed with copper. Though the mechanism is still confusing, it seems the copper sulfide is created on paper in two ways. The first one, solvable copper or copper compounds react with sulphur compounds on the paper layer surfaces, and then continue to grow on themselves. The second one is by spotting from the metal surface over the neighboring paper surface in imminent contact with it. Dielectric breakdown strength of the paper is reduced by copper sulfide. If it is adequate, it can end with arcing among strands, two or more, and consecutive burn through dielectric failure.

Corrosive sulphur has played a main role and it is supposedly the main factor in number of failures. Nevertheless, it is consequential to revise the notes from failures to be sure that located overheating or oversize voltage stress are not the major factors and corrosive sulphur a minor participant. [20]

3 Measurement techniques

3.1 Dissolved gas analysis (DGA)

DGA is a relatively cheap method used as diagnostic and maintenance tool for oil-filled transformers. It is possible to detect gasses dissolved from mineral oil and also from solid insulation. [21] [22]

Mineral oil is composed of hydrocarbon molecules. These molecules are formed by carbon (C) and hydrogen (H) atoms connected together by carbon-hydrogen and carbon-carbon bonds. Consequence of electric and thermal stress, these bonds are broken and free radicals such as H, CH, CH_2 and CH_3 are formed more quickly. By the recombination of these radicals, gases such as hydrogen (H_2), acetylene (C_2H_2), methane (CH_4), ethylene (C_2H_4) and ethane (C_2H_6) are formed.

The degradation of winding insulation is composed of three processes – hydrolysis, pyrolysis and oxidation, which lead to carbon monoxide (CO) and carbon dioxide (CO_2) formation. [23]

Gasses dissolved in oil starts forming at specific temperatures (Table 8)

Gas	Temperature
hydrogen (H_2)	> 150°C
acetylene (C_2H_2)	> 700 (500)°C
methane (CH_4)	> 150°C
ethylene (C_2H_4)	> 350°C
ethane (C_2H_6)	> 250°C

Table 8: Temperatures of gas formation [21]

The breakup of cellulose insulation starts at only less then 100°C. Therefore, the service temperature of the transformer must be less than 90°C. [21]

There are many methods for interpretation of gasses dissolved in oil. These are e.g.: Key gas method, IEC ratios method, Duval triangle method, Roger ratio method and Doernenbug method. The quantity of each gas is given in part per million (ppm). [24] [25]

3.1.1 Key gas method

This method is used for the prediction of different types of faults. The key gasses are hydrogen for corona in oil, methane for sparking, acetylene for severe overheating, carbon monoxide for overheated cellulose and ethane for local overheating. Interpretation of various key gasses is shown in Table 9. [24] [25]

Gas detected	**Interpretation**
Oxygen (O2)	Transformer seal fault
Carbon monoxide (CO) and carbon dioxide (CO_2)	Cellulose decomposition
hydrogen (H_2)	Electric discharge (corona effect, low partial)
acetylene (C_2H_2)	Electricd fiauhlt (arc), spark)
ethylene (C_2H_4)	Thermal fault (overheating local)
ethane (C_2H_6)	Secondary indicator of thermal fault
methane (CH_4)	Secondary indicator of an arc or serious overheating

Table 9: Interpretation of gas dissolved in oil [24]

3.1.2 Roger ratio method

This method uses relation between the four ratios. The fault diagnosis is shown in Table 10. [25]

C_2H_2/C_2H_4	CH_4/H_2	C_2H_4/C_2H_6	C_2H_6/CH_4	Fault diagnosis
< 0.1	0.1 – 1	< 1	< 0.1	Normal
< 0.1	< 0.1	< 1	0.1 – 1	Low-energy dencity arcing PD
0.1 – 3	0.1 – 1	> 3	1 – 3	Arcing-high-energy discharge
< 0.1	0.1 – 1	1 – 3	> 3	Low temperature thermal

Table 10: The gas ratio for Roger ratio method [22] [25]

3.1.3 IEC ratios method

This method is similar to Roger ratio method. C_2H_6/CH_4 was excluded because it indicates only limited temperature ranges of decomposition. In Table 11, there is IEC standard for interpreting fault types. [22] [24] [25]

C_2H_2/C_2H_4	CH_4/H_2	C_2H_4/C_2H_6	Fault diagnosis
< 0.1	< 0.1	< 0.2	Partial discharge
> 1	0.1 – 0.5	> 1	Low energy dicharge
0.6 – 2.5	0.1 – 1	> 2	High energy dicharge
< 0.1	> 1	< 1; 1 – 4; > 4	Thermal faults (T < 300°C; 300°C < T < 700°C; > 700°C)

Table 11: Diagnosis using the ratio methods (IEC 599) [24]

3.1.4 Doernenburg method

In this method four ratios are separated. The relation among them is shown in Table 12. [25]

CH_4/H_2	C_2H_2/C_2H_4	C_2H_2/CH_4	C_2H_6/C_2H_2	Fault diagnosis
0.1 – 1	0.01 – 0.1	0.3 – 1	0.2 – 0.4	Thermal decomposition
0.01 – 0.1	Not significant	0.1 – 0.3	0.2 – 0.4	Corona (Low intensity partial discharge)
0.01 – 0.1	0.75 – 1	0.1 – 0.3	0.2 – 0.4	Arcing (high intensity partial discharge)

Table 12: Gas ratio for Doernenburg method [25]

3.1.5 Duval Triangle method

This method was developed by M. Duval in the 1960s and its description is in Appendix B of IEC 60599:1999 standard. The concentration of three gasses is measured. These are methane (CH_4), acetylene (C_2H_2) and ethylene (C_2H_4). The percentage of each gas with respect to the total is calculated and represented as a triangular diagram subdivided into different parts, each representing a different fault (Figure 10). To use this method the concentration of all gasses must be higher than the level of measurability. [22] [24] [25] [26]

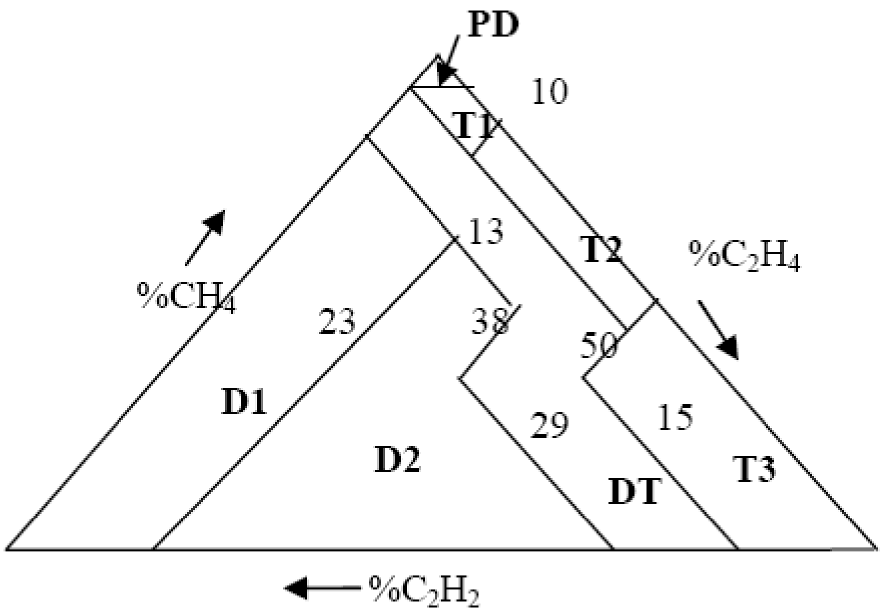


Figure 10: Coordinates and fault zones of the Triangle [24]

Limits and its signification from Figure 10 are summarized in Table 13.

Partial discharges (PD)	98% CH_4			
Low energy discharge (D1)	23% C_2H_4	13% C_2H_2		
High energy discharge (D2)	23% C_2H_4	13% C_2H_2	38% C_2H_4	29% C_2H_2
Thermal faults T < 300°C	4% C_2H_2	10% C_2H_4		
Thermal faults 300°C < T < 700°C	4% C_2H_2	10% C_2H_4		
Thermal faults T > 700°C	15% C_2H_2	50% C_2H_4		

Table 13: Zone limits [24]

3.2 Magnitude frequency analysis (FRA)

This is another new diagnostic method, which makes it possible to discover deformations and movement of windings without opening the transformer. You can imagine the winding as a substitute circuit compound of resistors, inter-coil capacities, capacities to the land and reciprocal and self-inductances. This circuit has specific inhibition which is frequency dependent. If there is a mechanical change of any part of substitute circuit, there is also a change of inhibition characteristic. These changes can occur as a result of transportation, severe insulation damage or fault currents. [1] [27]

Each transformer type has different effects of deformation on FRA. The different transformers can be affected differently by the same deformation type. There are several failure modes with different explanations of failure known.

Figure 11 shows the example of radial winding deformation. This failure is characterized by a pronounced change to the winding radial geometry. [27]

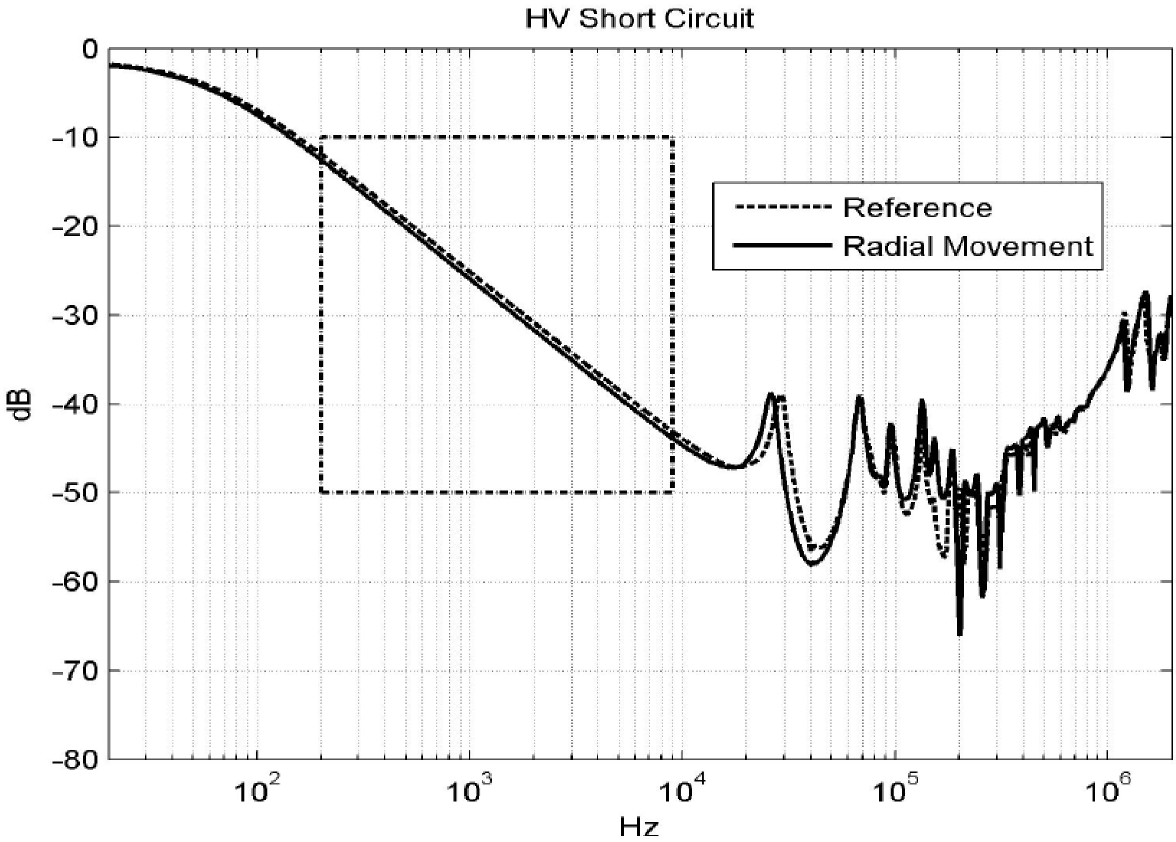


Figure 11: Radial movement response from HV short-circuit test [27]

3.3 High performance liquid chromatography (HPLC)

This is relatively new method based on analyses 2-furfural and similar furan derivatives which oil contains. These derivatives have to be extracted out of oil and its content indicates the degradation of cellulose. Measuring of the 2-furfural content is currently a very effective way of on-line monitoring. It is because of its strong correlation with DP.

Problems can appear when the transformer oil is filtered or replaced. Then it is not possible to measure directly the relation between DP and 2-furfural content. Nevertheless, the mechanical strength of the paper insulation does not change with the oil. Recording the data about changing oil is required, therefore analyzing of actual ageing status of the paper insulation can be done comprehensively. [1] [28]

3.4 Physical check of oil

During the years the quality of oil is getting worse. It is necessary to change the oil or do its regeneration. If this is not done, the life of paper insulation is reduced. [1]

3.5 Measuring of dissipation factor, capacity and insulation resistance

Measuring these factors is important for insulating system and its quality. The size of the dissipation factor is directly proportional to losses spread in dielectric. Its rises cause growing up of the temperature. It can lead to the destruction of insulation. [1]

3.6 Measuring temperature

As the temperature is factor which influences the ageing in the transformer the most, it is important to measure the temperature accurately. This measuring should be done continuously. The main methods used for measuring are the thermal simulation method, the thermal model method and the direct measurement method.

The thermal simulation method has quite a large error in comparison with the two others. The thermal model method is more accurate. However, there is still some error caused by the number of measured parameters. The most accurate method is the direct measurement. The sensors are in or near the winding to measure temperature. The problem is that the winding hot-spot may not be located. Therefore it is necessary to install a number of temperature sensors to measure temperature including the winding hot-spot effectively. [1] [29]

3.7 Detection of corrosive sulphur

There is a number of tests for diagnosing and measuring elemental sulphur and sulphur compounds in the oil samples. Some of them measure corrosive sulphur, elemental sulphur, total sulphur, inorganic sulfates and organo-sulphur compounds in oil. The testing methods are in the process of revising or have been already revised by standard organizations. Data from the corrosivity test are shown in Table 7. [20]

3.7.1 ASTM – D – 1275 A

This method for testing corrosive sulphur content has been used for many years. During this test, the oil is exposed to a copper strip and warmed up to a 140°C for 19 hours in a sealed surrounding. Whether the oil is corrosive or not shows the coloration of the copper strip.

Oxygen extremely affects the test. Unstable sulphur compounds are reduced by oxygen and thus cannot react with the copper strip. It is demanded to lead this test under the nitrogen conditions defined by method. Diagram used for evaluation the oil for corrosive sulphur is shown at Figure 12. [18][30]

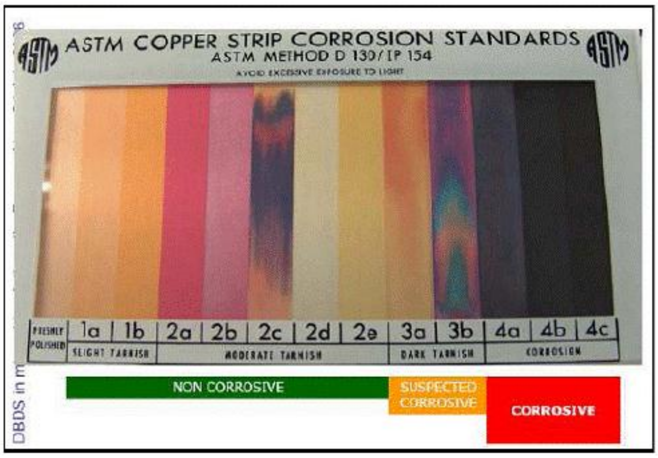


Figure 12: ASTM Copper Strip Corrosion Standard used to evaluate oil for corrosive sulfur [30]

3.7.2 ASTM – D – 1275 B

Although transformers passed the traditional ASTM –D 1275 A tests, some of them failed due to corrosive sulphur. In this case this method was modified to ASTM – D 1275 B in 2006. This method is similar to the traditional one. The oil is exposed to a copper strip and warmed up. Nevertheless, this method is more aggressive, the sample is heated to 150°C for 48 hours instead of 140°C for 19 hours. Thanks to this, the test is identies corrosive sulphur better (Table 14). Some of the sulphur compound break down and create more reactive compound due to longer exposition to intense heat. This newer method is now recommended for all transformer oils instead of the traditional method. [30]

Corrosivity of oil	**ASTM – D – 1275 A**			**DIN 51353**		**ASTM – D – 1275 B**
	19 h	48 h	72 h	18 h	168 h	48 h
Non corrosive	15	4	0	53	53	0
Suspected corrosive	25	15	2	Not applicable		0
corrosive	13	34	51	0	0	53

Table 14: Corrosivity test data obtained on 53 oils retrieved from failed Cu_2S contaminated apparatus [31]

3.7.3 Covered Conductor Deposition Test (CCD)

CCD tests started to be developed in 2004. This test is focused on the deposition of copper sulfide in the paper insulation. There are several variations of the CCD test.

The test is done in duplicate. At the beginning of the experiment, the oil is saturated by air before placing in the vial and then closed; therefore only oxygen is accessible. The oil is exposed to a conductor covered in Kraft paper and warmed up to 150°C for 72 hours. After the test the conductor and Kraft paper are excluded, cleaned and then both the conductor and the paper are visually inspected for the copper sulfide deposits. It is believed that the deposits on the paper, which cause degradation of dielectric strength, are primarily the reason of most corrosive sulphur failures. However, visible deposit on the paper, whether extensive, moderate or trivial, does not define if it is good or bad. Thus the deposits that form metallic sheen on the paper are regarded as “fail”. Others that do not are regarded as “pass”. Studies have proven that some transformer oils will pass the ASTM – D 1275 B testing, however fail the CCD test. As a consequence it is advised to fulfill both the tests. Failing the CCD test is more serious then failing the ASTM – D 1275 B tests. [30][32]

3.7.4 Dibenzyl Disulfide (DBDS)

A number of sulphur compounds are known to cause copper corrosion in transformers. Dibenzyl Disulfide is one of them. The concentration of DBDS in the oil is reduced by processes such as adsorbents, absorbents, and oil change-out. Concentration has to be below several mg/kg (ppm). If it is not, decomposition of the DBDS to benzyl mercaptan or DBDS copper complex can still cause corrosion of copper and form copper sulfide. DBDS itself may or may not be corrosive. There are different suggestions of researchers about reactions in which copper sulfide is seated on the copper surface.

In Doble engineering it is suggested that DBDS degrades through of cleavage of the disulfide linkage, as the temperature rises up in the oil the mercaptans are formatted in. The problem is that these breakdown products are very corrosive. Samples including DBDS have been tested. During the experiments at 110°C corrosion of the copper surface has appeared in a relatively short period. It was detected that in temperatures lower than 110°C it can also cause degradation. Temperatures about 80°C are sufficient to sulphur attack on copper in oils containing DBDS in just over 60 days. [33]

In Figure 13 there is the chemical structure of DBDS.

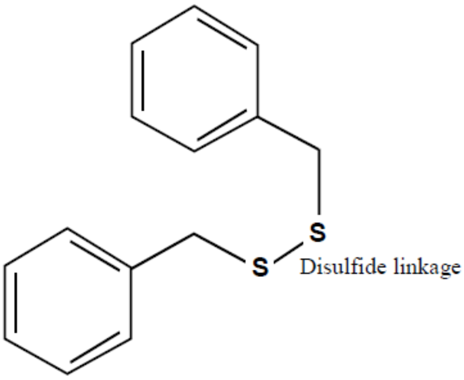


Figure 13: Structure of DBDS [33]

Here are some reasons why DBDS is in focus of research.

- The high concentration of DBDS was measured in oils involved in recent failures caused by corrosive sulphur
- Byproducts which degrade have been shown to be corrosive
- Reduction of DBDS concentration with time shows trending analysis in highly loaded transformers.
- Analysis of oils spiked with DBDS has shown that as concentrations of DBDS sink, the corrosive nature of the oil rises, especially in sealed systems. [33]

3.7.5 Mitigation methods

3.7.5.1 Passivators

Passivators, also known as metal deactivators, have been used in lubrication industry. Their use in the electrical industry is relatively new. They react with metal surfaces and dissolved metals such as silver and copper and decrease their speed of reaction with compounds in the oil. This involves oxidation reactions with organic compounds and also with corrosive sulphur. At Figure 14, you can see corrosive sulphur attack of copper conductor and ions without the use of passivators. [34]

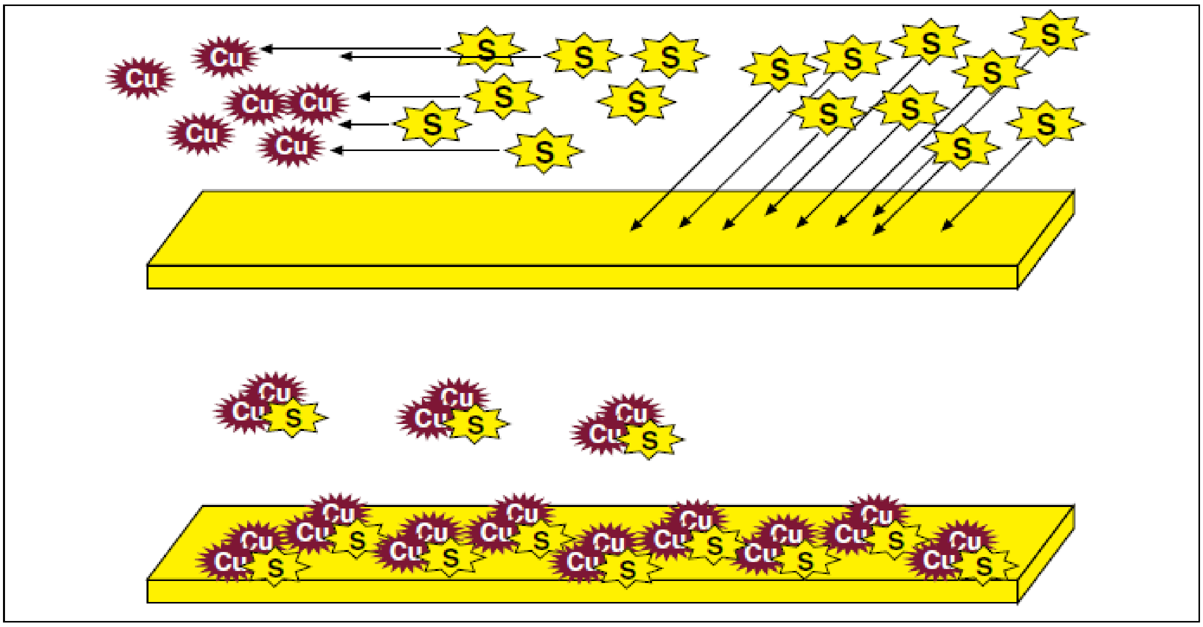


Figure 14: Corrosive sulphur attack of copper conductor and ions (Cu – copper, S – sulphur) [34]

Already in 1967, J. J. Melchiore and I. W. Mills of the Sun Oil Company suggested the first use of passivators in transformer oil. They did the accelerated oxidation tests which are concerned with the oxidation stability of transformer oils. There are two basic types of passivators: sulphur based and nitrogen based.

Nitrogen based passivators have been used in electrical insulating mineral oils and they have been mainly benzotriazole (BTA) or its derivatives. BTA is a granular solid at room temperature, beyond BTA derivative is liquid. It means that BTA derivatives are more easily meld with mineral oil then BTA which has to be heated and mixed to dissolve in the oil.

Nitrogen group of the BTA molecule is joined on the copper, silver and other reactive metal surface. This is so called chemical bonding. This process can be reversed upon the right occasions. The metal surface attracts passivators molecules which are kept at the reactive site, therefore the same site cannot be attacked by corrosive sulphur molecules (Figure 15). Free copper and silver ions and particles contained in the bulk oil can be also bind with passivators molecules. In reality, both, corrosive sulphur and BTA, as well as other compounds, struggle for the reactive metal sites. [34]

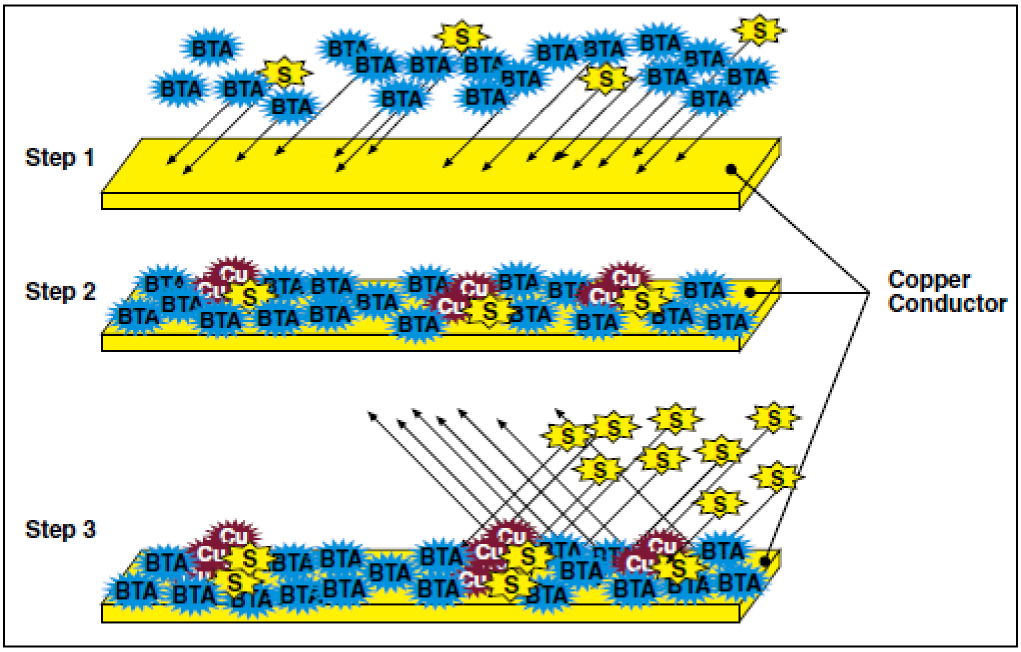


Figure 15: Action of passivator (BTA = BTA or its derivatives) [34]

The study on the application of passivators for control of corrosive sulphur reactions has been done mainly in laboratory. The long-term efficiency for moderating the cause of corrosive sulphur in apparatus is not known. Passivators slow down reactions of metal with corrosive sulphur as the research in Doble Laboratory has shown. Nevertheless, there was still the attack of corrosive sulphur, although the temperatures (110°C) were controlled and the passivators were added. The period of reaction was extended compared to experiments without the passivators. Immediately a copper sulfide is created on copper surfaces and loaded in the paper insulation. It cannot be taken away by passivators or other assets. In the apparatus there is a spectrum of reactions, so the passivators can be demoted or consumed. To keep adequate binding on the copper surface and to prevent the corrosive sulphur reaction, the passivators need to be added cyclically.

The new oils should be without consequential quantity of corrosive sulphur and they should pass more accurate modified version of the ASTM D 1275 test. The test should be performed at 150°C instead of 140°C and for 48 hours, not only 19 hours and it should also be with better sealing of the test bucket and better nitrogen purging, as recommended by Doble engineering. Passivators could be used to slow down corrosion in cases where the oils do not execute these stricter criteria. The best long-term approaches to solving the corrosive sulphur problem require a longer research. [34]

3.7.5.2 DBDS removal

Mitigation techniques do not effect corrosion that has already occupied place. Nevertheless, DBDS and benzyl mercaptans, which remain in the oil, are destroyed by this process. Adjunction of synthetic oxidation inhibitor to a concentration between 0.22% and 0.30% (by weight) is integrated into the process. It is because most oils with DBDS are not inhibited and thus some kind of stabilization for oxidation is required after the DBDS destruction process. Therefore, it is recommended to add synthetic inhibitors DBPC (BHT) or DBP.

One of the methods of removing DBDS from the transformers was performed by Doble engineering and it is described below.

Power Substation Services (PSS) prepared two sister GE transformers. Each of the transformers had around 900 to 1,000 mg/kg of total sulphur, however the level of DBDS in one of the transformers was undetectable and the other had only 7 ppm of DBDS. Sodium treatment processor technique was used. The oil was not corrosive, although there was a high concentration of sulphur. Each transformer was 667 kVA and contained about 350 gallons.

These transformers were excluded. There was no natural oil circulation. The DBDS concentration had to be homogeneous all the time, thus the oil in each transformer was circling nearly for half an hour. Oil samples were taken before the DBDS was added and after the completion of oil circulation process. The process is described only for findings of one transformer. The same process was fulfilled on both of them. The results were almost the same. The processing trailer contained about 400 gallons of oil through the piping and different pieces of equipment that assemble it. The inboard tanks were insulated to make sure the oil samples were taken from the transformer and not from the processing trailer.

The destruction process itself is shown at Figure 16. After the connecting of hoses to the transformer, the oil was pumped from the bottom valve into the processing trailer and warmed up. Then the reagent was injected to the oil to react with the DBDS. The oil gets through a degassing column and later to a stage to destroy any reagent which stays in. Lately in the centrifuge, the regent byproducts are removed. Afterwards the oil gets through the fuller's earth tanks, the vacuum dehydration column and the final filter before being regressed to the top of the transformer. [33]

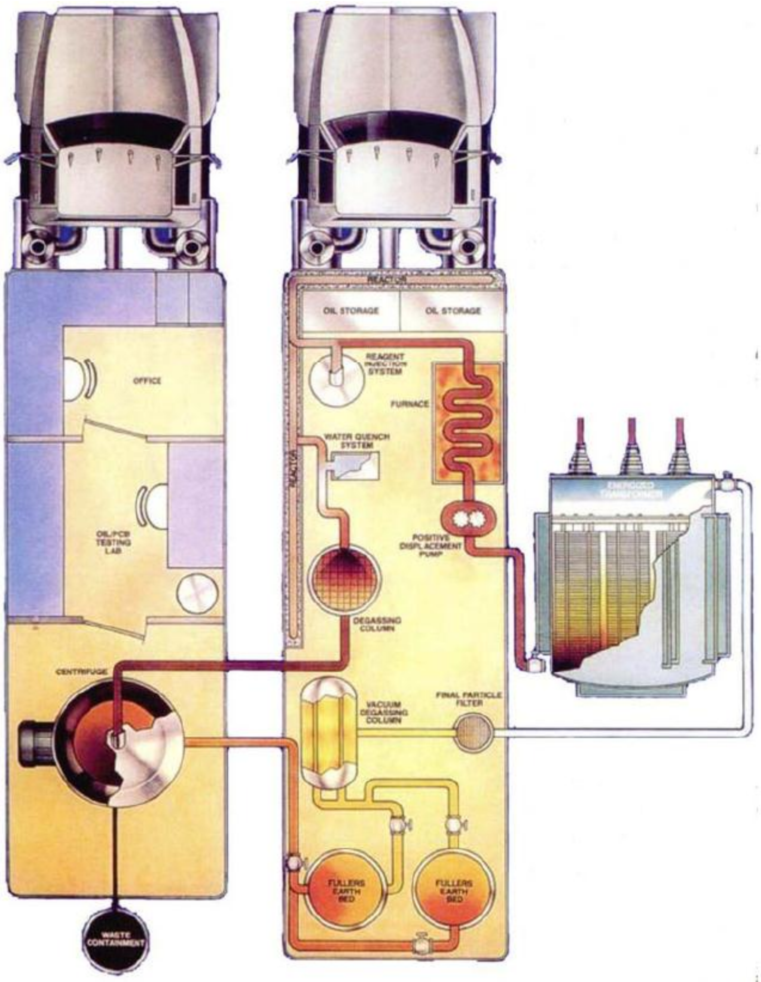


Figure 16: Oil processing flow for DBDS removal from transformer oil [33]

During the whole process samples were continuously taken. The oil passed through the processing trailer eight times. The first one was taken in the midpoint of the first pass and the last one after the completion of the eighth pass. With these samples of oil from the two transformers, the following tests were executed.

- DBDS concentration
- PCB Content
- Corrosive sulfur (ASTM D 1275B)
- Doble CCD+DT
- Oil quality tests
- Total sulfur

The results of DBDS concentration were very positive. Mixing the DBDS should have been kept on for a longer period of time, however, there was no DBDS present before it was added. Immediately it was added it was noticed. Despite unequal mixing, once the processing started, the DBDS was destructed quickly. During 4 passes the concentration decrease below 1 mg/kg. Also PCBs were destroyed at the same time. See Figure 17. [33]

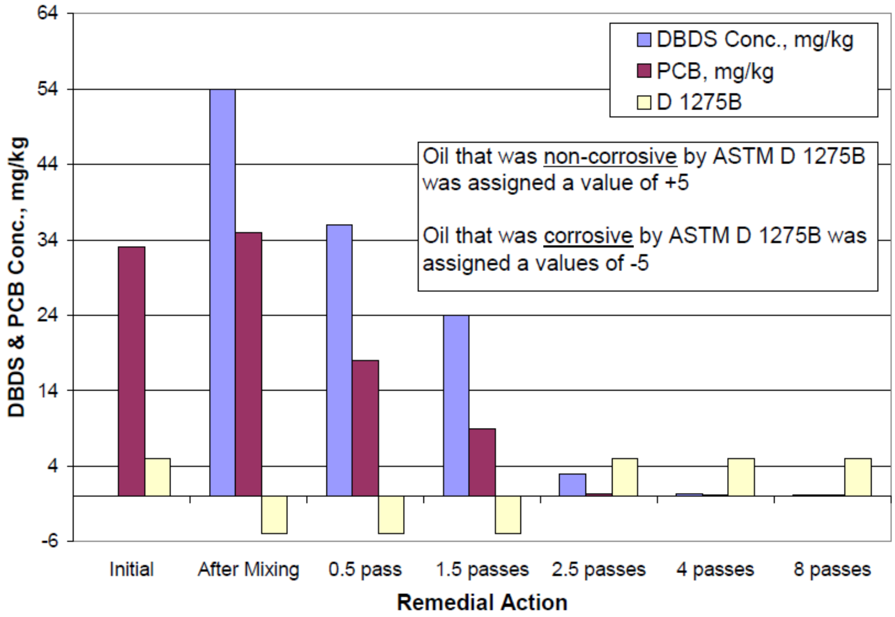


Figure 17: Destruction of DBDS and PCB [33]

4 Framework methodology

4.1 Introduction

The purpose of the methodology is to designate the main diagnostics methods used for the detection of transformer ageing impacts. These are focused on oil-paper insulating system of high voltage transformers and transformer bushings.

It is necessary to establish an effective system for the evaluation of risks during the transformer service life. This system should assure safe and reliable service with the minimization of maintenance costs and extend the life of the transformer to maximum.

All measured parameters should be periodically checked and saved. Based on the results the plan for maintenance is created. There are used SWs which are able to measure trends. Their monitoring is very important. If the owner does not collect historical data, it is very complicated to give relevant information about the transformer statement.

Each transformer has different parameters which are given by the manufacturer. It means each transformer is unique. Therefore, it is almost impossible to specify exact limits for a specific transformer. All the limits are mainly based on the collected data all around the world and from laboratory experiments.

4.2 Winding insulation

The life of the transformer is given mainly by paper insulation. Tensile strength is the main indicator of paper insulation quality. If the strength decreases under certain level, the dielectric loses its properties and the life is in the end. The correlation between tensile strength and degree of polymerization (DP) exists.

However, it is very complicated to get a cellulose sample from a transformer in service. The samples can be taken from specific parts, usually from bushings, during the maintenance of the transformer. There is also the possibility to put a measuring sample, which is easily accessible and there is no need to take a sample from the winding insulation. Another problem is, that DP of insulation is not equal everywhere. There are some parts where the heat is more intensive and we cannot take the sample from these parts. Therefore, the measurement from the accessible places is not precise. **It is required to take the sample and measure DP whenever it is possible.**

DP value	Significance
1,200 – 700	Healthy insulation
700 – 450	Moderate deterioration
450 – 250	Extensive deterioration
>250	End of life criteria

Table 15: DP and its significance

Table 15 shows the level of DP and its significance. If the value is above 700, the transformer can be carried on without any special restrictions. If the value is below 700, maintenance should be done more frequently. If the value is below 450, the risk of some failure is getting more and more possible. Therefore, transformer statement should be watched more precisely. If the value is less than 250, it is the end of transformer service life. Winding has to be wind on or the transformer has to be replaced by a new one.

It is less complicated to get an oil sample. Therefore the statement of paper insulation can be measured indirectly from the oil. A correlation between furans and DP has been found. Measuring furan compounds dissolved in oil is a relatively new method, especially measuring 2-furfural is important. The problem of this method appears after the replacement or regeneration of oil. That is why it is necessary to collect data about furans content to define the statement of insulation retrospectively.

2-FAL, ppm	Significance
0 – 0.1	Healthy insulation
0.1 – 1.0	Moderate deterioration
1 – 10	Extensive deterioration
>10	End of life criteria

Table 16: 2-FAL content and its significance

The correlation between furans and DP is shown in Table 16. If the value is below 0.1 ppm, the transformer can be carried on without any special restrictions. If the value is below 1 ppm, maintenance should be done more frequently. If the value is below 10 ppm, the risk of some failure is getting more and more possible. Therefore, transformer statement should be watched more precisely. If the value is more than 10 ppm, it is the end of the transformer service life. Winding has to be wind on or the transformer has to be replaced by a new one.

This method is still in progress and it is complicated to say if the results are really reliable in comparison with sample taking. However, **collecting data about furans content is recommended.** These data could be important for decision making in the future, when the method will be more developed and accurate.

The most influential factor in transformer is temperature. With growing temperature the amount of reactions in the transformer is increasing and the time of service life is decreasing. **Each transformer should have some device for on-line service temperature measuring.**

The measuring device should be installed to measure temperature especially at places with the suspected higher temperature (winding, where the cooling is not very efficient). Still, the temperature should be also measured in more accessible places. It is relatively cheap and effective. **The best option could be sensors installed in or near the winding.** Temperature can be measured continuously without errors. It is assured by more sensors around the transformer. Other possibility could be measuring by infrared measuring. However, this method gives us information only about the surface of the transformer. Therefore, the efficiency of this method is lower. The method with sensors is preferred prior to infrared measuring.

The temperature inside the transformer can cross the critical level, it is about 100 – 105°C, for a short time. Longer overloading of transformers leads to quicker degradation. There is the possibility that the load is switched off after some defined time. However, this system cannot be used everywhere. The transformer should be projected for specific usage not to be overheated.

As temperature measuring is very important, **the device for measuring of the temperature should be one of the first investments in the diagnostic of transformer. Temperature should be measured continuously during the whole transformer service life.**

Transformer can pass other tests without any problems. However, a failure can occur due to corrosive sulphur. Transformer construction contains materials including sulphur. Furthermore, not all sulphur compounds are considered as reactive. Nevertheless, the measuring of sulphur content is recommended.

To prevent sulphur formation, **passivators should be added into the transformer oil.** Some of the oil manufacturers add the passivators to the oil. If they do not, the passivators should be added separately. The content of tpassivators should reach at least 100 ppm (mg/kg). They react with cuprum on its surface. Therefore corrosive sulphur cannot attack its surface in the same place. Nevertheless, these attacks cannot be stopped at all, they are only mitigated. There is always a part which reacts with sulphur. **Further, due to inner reactions, the passivators have to be added after some time again.**

For sulphur content measuring in paper insulation, the Covered Conductor Deposition Test (CCD) is used. For detection sulphur in oil, there is method ASTM – D – 1275 B. The combination of these two methods shows whether the transformer is attacked by corrosive sulphur or not. It is more serious to fail CCD test than failing in ASTM – D – 1275 B.

The importance of DBDS concentration measuring is discussed. Only several mg/kg (ppm) can cause corrosion of copper and form copper sulfide. Therefore the measuring of DBDS should be done. **If the content of DBDS is detected, they should be immediately removed.**

All mentioned tests used for corrosive sulphur detection and mitigation should be done **every 2 years** with complex oil analysis.

Quite serious problems can cause distortion of winding. It can occur due to short circuits or during the transformer transportation. Magnitude frequency analysis (FRA) is a relatively new method used for winding distortion detection.

The analysis of the new transformer is done. Further analysis should be done after the transformer transfer to the service position. If everything is all right, this result serves as the reference value.

FRA should be done when the **new transformer is on the position.** Then it should be done periodically **every 2 years**, if transformer is in good condition. If it is not (e.g., DP is below 700…), it should be done **every year.** FRA should be also done **after any reparation**.

There are other parameters which should be measured. Among them belong resistance (R_{iz} [MΩ]) – it is the ratio of DC voltage connected to unloaded insulating system and direct current running through the system in specific time; polarizing index *pi* [-] – it is the ratio of resistances measured in different times. Further time is always in the numerator; capacity of winding *C* [pF]; dissipation factor of winding ($tg\delta$ [-]) – it is tangent angle of vector of capacity element of current and vector of total current; and time response T_r [s] – product of resistance and capacity of measured subject. **These measurements should be done every 2 years. If the transformer is older, 20 years and more, or some problems occur, it should be done every year or immediately.**

4.3 Insulating oil

The oil insulation should have good and constant properties during the whole service life. However, the oil is exposed to many influences; therefore its functionality is changing in time. Thus the oil has to be replaced or regenerated after some time.

The oil should be checked periodically during the whole life of the transformer, then also before the filling of the transformer, before the transformer is in service, during the guarantee time, after any manipulation with oil and before and after regeneration.

It is known that gasses are formed in transformer oil during the time. It is important to know their content. Dissolved gas analysis (DGA) is a powerful diagnostic method which gives us information about inner statement. Gases such as hydrogen (H_2), acetylene (C_2H_2), methane (CH_4), ethylene (C_2H_4) and (C_2H_6) are formed. Each gas has a specific failure meaning. There are several methods for the interpretation of dissolved gasses. The special SW, where the combination of the DGA methods is used for evaluation, is used for evaluating nowadays.

The DGA is also used for the measurement of oxygen (O_2) and also carbon monoxide (CO) and carbon dioxide (CO_2) as factors of insulation ageing process. Nevertheless, new methods for measurement of dissolved gasses are being developed. Those are, e.g., Quantitative Diluted Gas Analysis (QDGA) and Gradient Diluted Gas Analysis (GDGA) which measure dynamic changes in oil instead of static like DGA.

DGA analysis should be done continuously. If there is not any system for on-line monitoring, measuring should be done every ¼ year. It is very important to watch the development of trends, which gives us valuable information and eventual warnings.

Another factor which should be measured is moisture content, which decreases insulating properties of dielectric. Moisture is always present in transformer. With the increasing content of moisture, the compounds in the oil are dissolved more quickly, especially in combination with higher temperature. Water is mainly contained in solid insulation. When the temperature is rising up, water is relocating to the oil insulation. If the temperature is decreasing, water is returning back to the winding insulation. Therefore the measuring has to be done while the transformer is in service for some time to have relevant information about water content in the transformer.

The C2/C50 measuring is used for the determination of water presence in the transformer oil. The ratio of the capacity measured in 2 Hz (C2) and in 50 Hz (C50). The dependence of relative permittivity is used. If the insulation is dry, the capacities are close. If the content of the water is higher, there is bigger difference between these capacities.

The method return voltage measurement (RVM) can be also used. The problem is that this method is less sensitive to disturbances by external noise. It can lead to mistakes during the measurement.

If the transformer has water content **higher then 2%, it should be dried**. However, drying of the transformer cannot be jump. It is not possible to dry transformer with water content higher than 5% to 1%. **Measurement of water content should be done every year.**

The **complex analysis should be done every two years**. **Older transformer should go through it every year.** Complex analysis includes measuring of color and cloud of insulating oil, content of inhibitors [% of weight], break-down voltage U_p [kV/mm], deposits dissolved in gas [-], acidity number AN [mg KOH/g]. Results of these measurements give additional information about transformer oil statement. Analysis methods mentioned in the part above should be measured as well.

If the transformer oil does not fulfill the limits, it should be replaced or regenerated.

4.4 Bushings

The parameters measured on bushings are capacity and dissipation factor. Each bushing is specific. Therefore, it is required to know the limit for capacity and the dissipation factor of the bushing from the manufacturer.

Measurement should be done when the transformer is new and at the position. Further during the service, if there is gauging terminal and after the replacement or any manipulation with bushing.

4.5 On-line vs. Off-line

It is very important to do on-line monitoring, as it gives us valuable data during the service life of transformer without interruption of service. Its advantage is cooperation with SW for on-line diagnostic and immediate results. Thanks to that it is possible to make a decision about the maintenance and the transformer current statement. However, **on-line monitoring does not replace off-line monitoring.** Off-line monitoring is required as well. It is done periodically and gives us more detailed information.

Conclusions

The consumption of electricity causes increasing loads of transformers. Therefore life management theory, measurement techniques and framework methodology for life management have been presented in this diploma thesis.

For the analysis of the samples from a device out of control there is off-line monitoring. On-line monitoring, when the device is still in service and collected data are evaluated is of the same importance. Thus problems can be solved immediately.

The insulating system of transformer consists mainly of oil-paper insulation, where the paper insulation quality designates the life of the transformer. There are many factors influencing the quality. The most important are temperature, content of gases dissolved in oil, humidity and oxygen.

Winding insulation consists of paper, which is based on cellulose. Its degradation causes losing tensile strength which has a strong correlation with the degree of polymerization (DP). It is used for the assessment of quality. The new Kraft paper has DP between 1,200 and 1,500. During time it decreases to the value about 200. When it reaches this value, paper loses all tensile strength and it means the end of the life of the transformer.

As it is very complicated to get into the transformer in service to get a paper sample to measure its DP, the correlation of DP with furans dissolved in oil can be used. Furan derivatives content has strong correlation with DP, especially 2-furfural (2-FAL). While the DP is decreasing, the 2-FAL content is growing up. When the DP reaches the value of around 400, the content of furans starts to increase more intensively. As soon as its value is more than 10ppm, it signifies the end of the life of the transformer. A correlation between furans and moisture content in solid insulation has been found as well. The influence of moisture affects DP and 2-FAL concentration. At the same temperature, and higher moisture, the content of 2-FAL is growing up faster than with lower moisture. It means that the influence of moisture content on furan concentration looks more extensive than higher temperature.

The dangerous factor influencing the life of transformer is corrosive and reactive sulphur content. Almost all parts of a transformer contain sulphur. However, not all sulphur is considered to be corrosive or reactive. In oil there are five groups. The most reactive of all is elemental sulphur, which is called corrosive. The rest is reactive. Nevertheless, even stable sulphur compound can get reactive, if it is exposed to higher temperatures.

Measuring transformer parameters is essential. There are few methods described in this thesis. The most important is temperature measuring because temperature affects all the parts of a transformer. Dissolved gas analysis (DGA) is one of the most known and most important techniques to detect failure in a transformer. This method measures gasses dissolved in oil. The content of each gas has different failure significance. It is important to trace trend. Another method is magnitude frequency analysis (FRA), which shows, e.g., if the winding has not been moved after moving the transformer during the transportation. Quite a new method used for DP measuring is High performance liquid chromatography (HPLC). The content of furans dissolved in oil is measured. A correlation between them and DP exists. The failures of transformers due to corrosive sulphur led to the development of new methods for detecting corrosive sulphur content. Nowadays, it is recommended to do ASTM – D – 1275 B, where the content of sulphur in oil is measured, and Covered Conductor Deposition (CCD) test, where the copper sulfide deposits are visually inspected. For mitigating of corrosive sulphur attacks, the passivators are used. As a passivator, mainly benzotriazole (BTA) is used. It is mixed into the oil and then it reacts with copper. Thus sulphur compounds cannot react anymore. However, if the places are already attacked by sulphur, it cannot be replaced.

In the end, there is the framework methodology for life management of transformer. It is based on the data and knowledge the author has obtained during writing this thesis.

Because of the importance of transformer service life, researchers are trying to develop other new measuring methods or currently improve the old ones. Therefore life management is a quickly developing branch which deserves consideration not only nowadays, but also in the future.

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