

Tutorial on Rehabilitation and On-Line Processing of Transformers

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POWER TRANSFORMERS.WHAT'S THE PROBLEMS?

- **Equipment is getting older, 30-60% of large transformers are behind the rated life.**
- **24,000 Critical Transmission Transformers in the world**
- **Significant organizational changes in electric Power companies. Pressure to safe money**
- **. Lack of Expertise & Experts**

NEW MAINTENANCE CONCEPTS. WHY?

- **Economic Pressure to Reduce Maintenance but verify Reliability and extended Life**
- **Move from Time-Based to Condition –based and Reliability Centered Maintenance**
- **Preferential On-Line Methodologies:Monitoring & Processing**
- **New Findings about Mechanisms of Degradation**
- **New Test Methods and Methodologies**

WHAT'S HAPPENING?

- Over 80% of Failures caused by Degradation of Transformer's Condition-Different Aging Disease
- Only 5 % of Failures an Excessive Aging of Cellulose involved
- Accelerated Deterioration of Components: Bushings & LTC
- Over 70% of Failures caused by reversible mode defects and could be corrected In-field

Degradation of Transformer Insulation

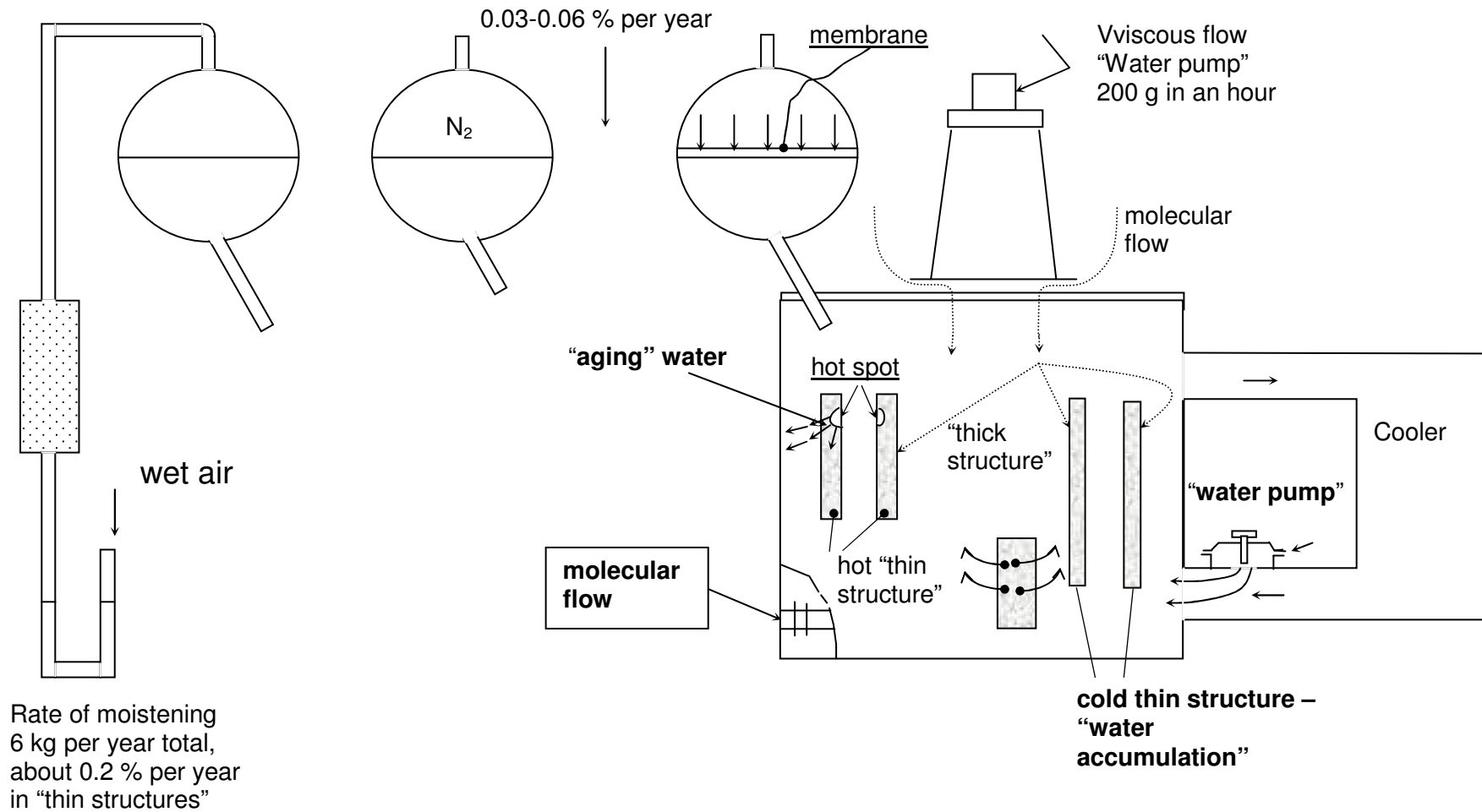
AGENTS OF DEGRADATION

Water, oxygen, oil aging products) and particles of different origin are agents of degradation which can shorten transformer Life significantly under impact of thermal, electric, electromagnetic and electrodynamic stresses

Process of Deterioration

Processes of insulation deterioration involve slow diffusion of water, gases, and aging products and therefore affect basically only a part of insulation structure, the so-called thin structure (paper insulation of turn and coils, pressboard sheets, etc.) which comprises typically 40-60% of the total mass.

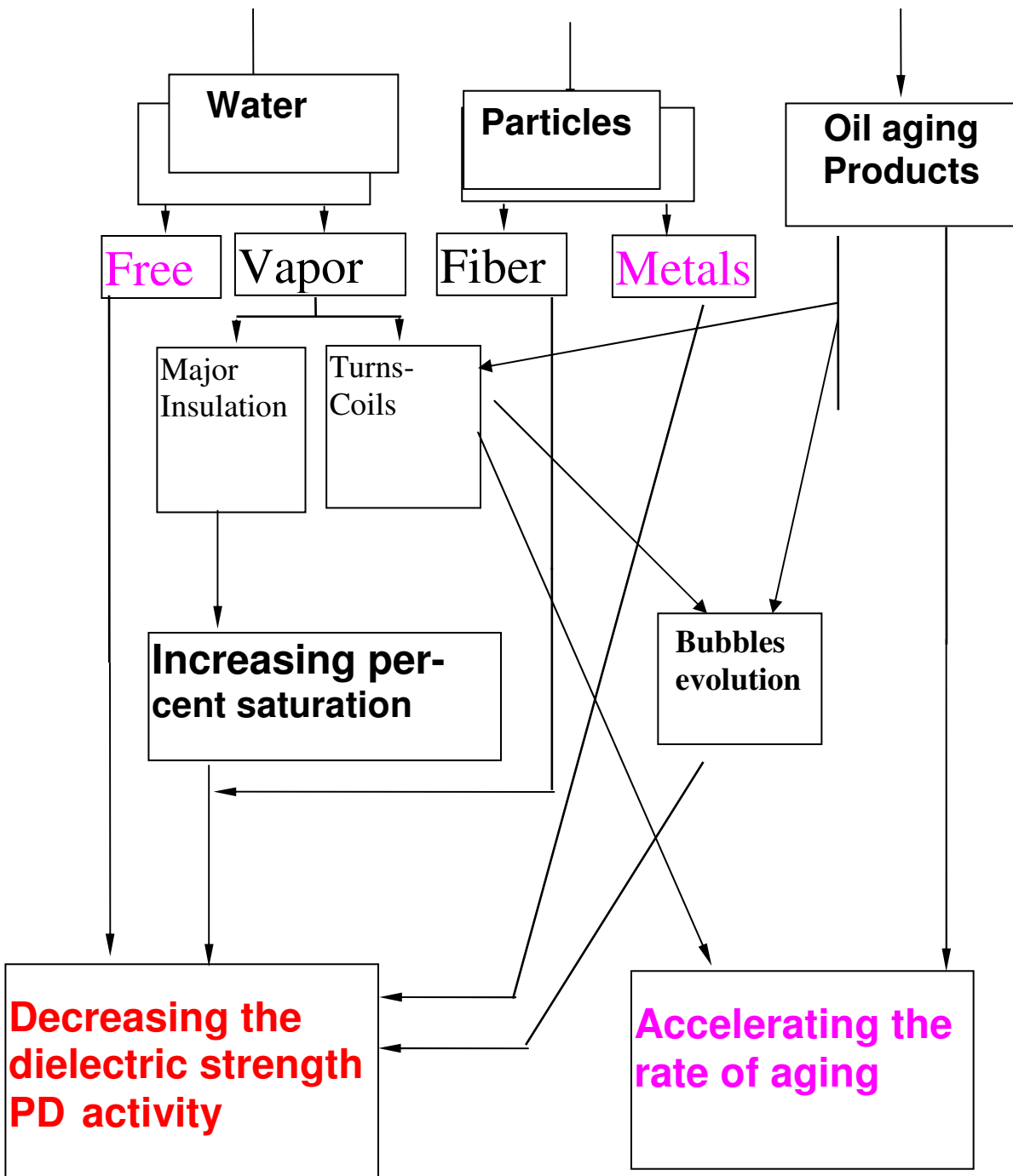
Sources of Water Contamination



Upper Estimate of the Rate of Water Contamination

Conditions	Rate of Water Contamination
<p><u>Direct exposure to air:</u> a) RH* = 75%, 20 °C b) RH* = 40%, 20 °C</p>	<p>Sorption of water in pressboard of 1000 m² 13,500 g in 16 hours 8,100 g in 16 hours</p>
<p><u>Viscous flow of air</u></p> <ul style="list-style-type: none"> • Adequate sealing • Insufficient sealing 	<p>600 g per year 15 g in a day</p>
<p><u>Operation with open-breathing conservator</u></p>	<p>6,000 g per year</p>
<p><u>Insufficient sealing with rain water present</u></p>	<p>200 g in an hour as free (liquid) water</p>

Typical case: Free-Breezing, 15 years in service, 2.5-3.0 % moisture in 1000 kG of thin structure; totally 30- 40 kG of Water



Dangerous Effect of Degradation Factors

WATER IN TURN INSULATION

Accelerates aging decomposition, and depolymerization of cellulose is proportional to the water content.

This process becomes much more dangerous in presence of acids and non-acid polars

Rapid rise of temperature causes rapid evaporation of absorbed water followed with rapid rise of vapor pressure and bubbles evolution

The criteria of bubbling depends on interfacial tension of the oil

$$P > 2\sigma/d$$

Defective Condition of Dielectric System

- **Increase of the relative saturation** over 40-50% (considering the level of particles contamination) in the range of operating temperatures.
-
- ***Water in solid insulation*** in the compliance with the above stated level of water in oil. The corresponding water content in barriers exceeds typically 1.5-2%.
-
- ***Water in winding turn insulation*** that may result in bubble evolution during overloading ($>1\%$), considering Interfacial Tension of Oil

Defective Condition of Dielectric System

- **Particles in oil:** the number of particles in the range 5-150 μm more than 3200 in 10 ml of oil The presence of visible and conducting (metals, carbon) particles
- **Critical oil aging:** possible appearance of sludge in oil in the period between the tests. The end of the induction period (trend of accelerated degradation). The presence of acids and non-acid polar that accelerate cellulose decomposition.
- **Bubbles in oil :** water vapor, nitrogen
- *pumps cavitation*
- C_2H_2 generation due to high temperatures ($>800^\circ\text{C}$) when bubble evolution is practically an inevitable phenomenon.

Defective Condition of Dielectric System

- Reduction of Tensile strength of the paper
The end of life is typically 50% of the initial strength of paper
- Abnormal Reduction of DP-
.The end of life is typically considered the DP of 200-150.
- High concentration of CO (>500-800 ppm) , CO₂ (>3,000-5,000)
- low (typically less than 3) ratio of CO₂/CO
- Presence of elevated amount of furanic compounds
- (typically concentration of furfural over 1 ppm)
- Abnormal rate of furans evolution (typically over 50-90 ppb per year)

Dielectric Life is Shorter Than Mechanical

HOT SPOT TEMPERATURE,C	ESTIMATED LIFE TO DP=200 YEARS	ESTIMATED LIFE TO REDUCTION OF DIELECTRIC STRENGTH BY 40 %
80	6229	124
100	50	22.1
110	17	10
125	4	3.3
140	1	1.16
160	0.19	0.32

Rehabilitation of Transformer Insulation

The goal of Transformer Rehabilitation

- Restoration of Dielectric Safety Margin
- Slow down the rate of Deterioration
- Reconditioning Insulation Components

Objectives of Processing

RECONDITIONING THE NATURALLY DETERIORATED TRANSFORMERS:

- Aged oil,
- Contamination of cellulose insulation with oil aging products
- Saturation with air
- Moisture contamination
- Particles contamination

Objectives of Processing

REHABILITATION OR MAINTAINING THE FAIRLY GOOD HEALTH OF DEFECTED TRANSFORMERS

- Having a source of gas generation (e.g., localized overheating)
- Having source of particles (carbon, metal) contamination
- Having severe moisture contamination of solid insulation
- Having severe contamination with sludge or other aggressive oil aging products

Objectives of Processing

REHABILITATION OF THE INSULATION SYSTEM AS A PART OF LIFE EXTENTION PROGRAM

- **Remove Water**
- **Degassing (Oxygen removing)**
- **Remove Particles**
- **Remove Oil Aging Products from Oil**
- **Remove Oil Aging Products from solid Insulation**

Restore Dielectric Margin

Reduce the Rate of further Deterioration

INSULATION REHABILITATION PROGRAM

- **Drying out**
- **Filtering (particles removing).**
- **Oil reclaiming – removing of aging products.**
- **Insulation regeneration / De-Sludging**
- **Degassing and re-impregnation of the insulation**
- **PCB removing**

Drying out

Typical Condition of Transformers to be subjected to Drying out

Typical Condition	Typical Case
<i>Free water on the bottom Insulation is comparatively dry</i>	<i>Water Penetration through loosed sealing</i>
<i>Concentration of Water in the vicinity of surface</i>	<i>Exposing of insulation to air during installation or repair</i>
<i>Water (3.0-3.5%) in thin structure –pressboard barriers</i>	<i>Prolong Operation with free- breathing system</i>
<i>Water in thin structure 6-8% In thick structure up to 3-4%</i>	<i>Postfailed unit being exposed to outdoor air for a long time (year)</i>

Methods of Drying out In-Field

- ❖ ***Circulation of hot dry oil;***
- ❖ ***Vacuum only ("cold drying");***
- ❖ ***Heat / vacuum cycles;***
- ❖ ***Hot oil spray;***
- ❖ ***Combined low-frequency heating / oil circulation vacuum process;***
- ❖ ***Combined oil spray / hot air / vacuum / cycles process;***
- ❖ ***Combined oil spray / dry air.***
- ❖ ***Vapor Phase***

DRYING OUT OF HV TRANSFORMERS.HEATING METHODS.

HEAT AGENT	METHOD
<p><u>Hot Air</u> →Insulation (Core & coil)</p>	<ul style="list-style-type: none"> • Continuous circulation of hot air • Circulation of hot dry air as a stage of combined hot air / vacuum drying process.
<p><u>Oil</u> → Insulation (Core & coil)</p>	<ul style="list-style-type: none"> • Circulation of hot oil as the main part of drying. • Circulation of hot oil as a stage of combined process. • Oil-spray: • Hot oil bath – heating bottom part of core
<p><u>Internal Losses</u> Conductor⇒Oil ⇒ Barriers</p>	<ul style="list-style-type: none"> • Flow through DC current (typically HV winding). • Short-circuit losses – low-frequency heating (LFH)

HEATING PROBLEMS

- Heat dissipation (outside) – effective thermal insulation is necessary.
- Leveling oil temperature within the tank (heating through oil).
- Uniform heating the insulation by the hot oil spray process.
- Overheating and aging the oil during hot oil-circulating process.
- Risk of overheating the winding insulation under flowing current:

DRYING.PHYSICAL CONSIDERATION.



◆ Moisture drying forces:

- Moisture gradient (isothermal diffusion);
- Temperature gradient (thermodiffusion);
- Pressure difference (convection diffusion, viscous movement of moisture in macrocapillaries).

*Moisture/ temperature gradients direct to one-way – drying process acceleration;
contrarily – process retardation.*

ESTIMATION OF DRYING PARAMETERS

The minimum equilibrium water content $W_e = \frac{W_f - KW_i}{(1-K)}$

K – remnant of water after drying;

W_f, W_i – final and initial water content.

E.g. **W_i = 3%, W_f = 0.5%, K = 0.1, W_e ≅ 0.22**

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DRYING PARAMETERS

- *Insulation drying temperature*

- high enough to achieve final dryness;
- low enough to prevent an essential loss of life;
- optimal drying temperature 80-90 C

- *Residual pressure*

Water equilibrium in "Cellulose – vacuum" & "Cellulose-oil-Dehydrator system"

At 80 °C $W_e = 0.22\%$ can be achieved under pressure $P < 1$ mm Hg

DRYING PARAMETERS

Consider Moisture Transfer Potential $\phi_W = \frac{P}{\sqrt{T}}$

$$\frac{P}{\sqrt{T}} \text{ Paper} \geq \frac{P}{\sqrt{T}} \text{ drying medium} \geq \frac{P}{\sqrt{T}} \text{ dehydrator}$$

- *Residual pressure*

Moisture gradient above equilibrium value

At 80 °C $W_e = 0.22\%$ can be achieved under pressure $P < 1$ mm Hg

Drying Time

- A time for drying the thickest pressboard can be taken as a time of whole process on given conditions:

d – insulation thickness;

W_0 – initial moisture content; W_f – final moisture content;

D – diffusion coefficient for given temperature, residual pressure;

K – remnant moisture.

$$\frac{W_f - W_e}{W_0 - W_e} = K = F\left(\frac{Dt}{d^2}\right)$$

Roughly
$$t \cong \frac{d^2}{D \cdot p^2} \cdot \ln K \cdot \frac{p^2}{8} \cdot (-1)$$

Criteria of Drying out Finishing

- Agreement with equilibrium parameters:
 - *temperature of the thickest wet insulation component;*
 - *residual pressure.*
- Rate of moisture removed under equilibrium condition.
- Rise of pressure after the insulation exposure to equilibrium condition.
- Water content in insulation model (pressboard patterns).

Criteria of Drying out Finishing

- Agreement with equilibrium of participant media:
 - *oil – water content (relative saturation);*
 - *air – water vapor pressure (dew point).*
- Agreement with drying time.
- Indirect criteria- dielectric characteristics:
- **dissipation factor, DC resistance, polarization index:**

Corresponding to final water content, typically 0.5 %.

Regeneration of composite Dielectric System

Typical Condition of Transformers to be subjected to Regeneration

- Aged Oil –degree at what sludge evolution may be expected
- Substantial amount of acids and non-acid polar
- Discoloration of the pressboard/paper
- Localized Deposit of Sludge on insulation zones under excessive dielectric strength (typically invisible without dismantling)
- Symptoms of Substantial Increasing Surface Conductivity

Sludge is the most dangerous Enemy

- **As impurity** – reduces oil dielectric withstand strength (like particle)
- **As semiconductive sediment** – reduces impulse withstand strength
- **As extreme sour**-effective killer of *new oil and cellulose insulation*
 - *Sludge acidity: 30...300 mg KOH /g*
- **Different sludge:**
 - *from different oil;*
 - *from the same oil at different temperature;*
 - *under different dielectric stress*

Aggressiveness is more important than quantity.

SOLUBILITY OF OXIDATION AND DECAY PRODUCTS IN DIFFERENT OILS

- Old empirical rule: a substance is dissolved in a similar solvent.
- Transformer oil can dissolve oil-aging products to some extent.
- Solvent action of oil depends on:
 - **aromatic content -the more – the better;**
 - **molecular weight (viscosity) – the less – the better;**
- Some detergent (regenerative oil) is necessary to remove aging products effectively.

How to remove oil aging Products out of Insulation?

- **Use a special regenerative oil:**

Utilization of Regenol instead of transformer oil for some time (months, year).

A detergent is transformer oil with some cleaning agent.

- Flush-out insulation for a certain time to remove aging products.

- **Improve detergency of operating oil:**

- by means of some special cleaning additives;
- by means of establishment of special condition:

a) Maintaining a low concentration of oil decay by reclaiming;

b) Maintaining a high temperature of oil to improve its solubility.

METHODS OF TRANSFORMER DESLUDGING

Regenerative oils techniques

Temporal operation with regenerative oil

- ◆ Refilling transformer with regenerative oil (Regenol).
- ◆ Flushing very contaminated core and coils before refilling.
- ◆ Operation for 10...20 months under special control.
- ◆ Refilling with stable transformer oil.

METHODS OF TRANSFORMER DESLUDGING

Desludging as a part of rehabilitation process

- ◆ Using Regenol as a technological oil during "oil-spray – vacuum cyclic" process, **t = 85 – 90 °C**.
- ◆ Cycle of heating means at a time cycle of desludging.
- ◆ Monitoring of oil aging products during the process.
- ◆ Correction the desludging and washing process with dependence of insulation contamination.
- ◆ Reclamation of Regenol during high vacuum drying process (if necessary).

METHODS OF TRANSFORMER DESLUDGING

- "Fluidex" technique

Desludging by means of desorption of aging products into oil being freshly, regenerated through adsorbed percolation columns.

Energized transformer to use loading heat is preferable.

Heating the oil above its aniline point (> 78 °C).

Reactivation the clay after obvious appearance of aging products.

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METHODS OF TRANSFORMER DESLUDGING

Fullers Earth reclamation

- hot oil circulation to dissolve sludge;
- oil reclamation with fullers earth passes;
- precipitated sludge removed by hot oil circulation;
- oil heated to 90 °C before returning to transformer.

Concepts of Oil Restoration

- Oil in Power Transformers is of low-oxygen medium
- The unstable molecules (initially responsible for limitation of oxidation stability) are oxidized in the first turn
- Removing the oil decay products can make the restored oil better than a new one
- Incomplete reclaiming (presence of residual aging products) can make transformer Life shorter

Monitoring of Insulation Regeneration

Parameters	During the Process	After the Process	Criteria after the Final Process of Oil Reclaiming
Color	Yes	Yes	0.5-1.5
Neutralization Number		Yes	IEC 296
Saponification Number	Yes	Yes	< 0.1
No-acid polar IR scan		Yes	absent
Resistivity	yes	Yes	IEC 296
Dissipation Factor	yes	Yes	IEC 296
Interfacial Tension		Yes	IEC 296
Oxidation Stability		Yes	IEC 296

On-Line Processing

On-Line Processing History

- Permanent regeneration system (cartridges filled with silica-gel) have been specified in the USSR for over 40 years
- Permanent filter systems on the 1150 kV units-15 years
- On-Line drying out of 500kV transformers utilizing molecular sieves was introduced in early 70th
- On-Line degassing of 330-750 kV transformers –20 years

On-Line Processing History

Appearance of Special Modern Technique

- Fluidex
- Pall
- Velcon
- Dry Keep (South Africa)

Technical and psychological obstacles to wide implementation of On-Line procedures:

- ***Risk of failure due to possible introduction into the tank air, bubbles, particles or other impurities; loss of oil level; occurrence of static electrification***
- ***Risk of failure while processing “unhealthy” transformer***
- ***Very long time (in some cases) of treatment (costly process***

***If a transformer keeps functional serviceability
any improvement of its condition may be performed
without de-energizing.***

***The problem is only whether safety measures are sufficient
ones.***

How to minimize the risk of Failure

- *The system shall not incorporate a vacuum process*
- *Do not allow air permeate into the tank:*
- *Do not allow oil to splash.*
- *Do not allow foam ingress into the tank*
- *Do not allow particles ingress into the tank*

How to minimize the risk to loose of oil during processing

- Consider minimal volume of oil in the transformer, taking into account possible loss of oil during reclamation (replacement of waist clay)
- Watch oil level; consider the oil level gauge
- Consider arrangement of a metal standpipe to minimize the loss of oil
- Consider automatic shut down controls

ESTIMATION OF THE PROCESSING TIME

A process of reconditioning by means of circulating oil through processing equipment is of exponential mode

$$\frac{n(t)}{n_o} = \text{Exp.} \left(-\xi \cdot \frac{t}{\tau} \right)$$

n_o and $n(t)$ --initial and final concentration of contaminants

ξ -Coefficient of purification efficiency t -time of processing

τ -time constant;

$$\tau = V/Q$$

V -oil volume in the transformer

Q-rate of flow

Parameters to be monitored

- **Ratio of final and initial concentration of contaminant;**
- **Ratio of flow rate and total volume of oil in the transformer;**
- **Ratio of inlet and outlet concentration of contaminant per one pass of treatment into the processing machine**

Gauges

- **Pressure on the suction side (cavitation)**
- **Differential pressure**
- **Temperature**
- **Flow meters**
- **Moisture Sensor**
- **PD sensor**
- **Gas sensor**

DRYING OUT OF INSULATION THROUGH DRYING THE OIL

DRYING OUT OF INSULATION THROUGH DRYING THE OIL

On-Line procedures are definitely more efficient than Off-Line because of possibility to utilize internal losses of a transformer as source of heating.

On-Line processing may be really very efficient in case using molecular Sieves and Passive methods of Processing

DRYING OUT OF INSULATION THROUGH DRYING THE OIL

To achieve moisture content in the pressboard < 1% by means of dry oil circulation

Oil percent saturation shall be less than 5 % (15 ppm at 70 C or 10 ppm at 60 C)

Moisture content in de-Hydrator (“water removing filter”) shall be 0.5 %

Sorption Capacity of Molecular Sieves, g/100g

<i>Pressure Pa</i>	<i>Temperature C</i>				
	<i>0</i>	<i>25</i>	<i>50</i>	<i>100</i>	<i>150</i>
<i>0.013</i>	<i>2.0</i>	<i>1.6</i>	<i>0.4</i>	<i>0</i>	<i>0</i>
<i>.13</i>	<i>4.8</i>	<i>3.2</i>	<i>2.0</i>	<i>1.0</i>	<i>0.4</i>
<i>1.33</i>	<i>14</i>	<i>6.0</i>	<i>3.8</i>	<i>3.0</i>	<i>2.2</i>
<i>13.3</i>	<i>18</i>	<i>15</i>	<i>8.0</i>	<i>3.6</i>	<i>3.2</i>
<i>133</i>	<i>18</i>	<i>18</i>	<i>16</i>	<i>6.0</i>	<i>3.6</i>

Conclusion

- Aging effect on Power Transformers is basically reversible contamination causing degradation of dielectric safety margin
- Irreversible Loss of Life is still not a very critical phenomenon
- The necessary Rehabilitating Processes shall be aimed:
 - to restore the Dielectric Margin by means of removing water, particles, gases, and oil aging products which affect dielectric withstand strength,
 - to slow down of Degradation Rate by means of removing Oxygen, water, acids and non-acid polar, surface active components and other aggressive components

Conclusion

- There have been experience of fully restoration of transformer condition in-field
- There is a prominent opportunity performing all the necessary processing on energized transformer using advantages of operating condition
- Capturing and summarizing the knowledge, and elaboration of practical recommendations on Rehabilitation Processes especially on On-Line Processing Procedures could be objectives of Joint activity of WG SC12 and WG 15.01

