Spezifikationen und wichtige Eigenschaften von Transformatorenölen im Hinblick auf eine optimale Einsatzdauer

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Johan received MBA in International Economics and Marketing from Gothenburg University School of Business, Economics and Law in 1992 and MSc in Chemical Engineering from Chalmers Technical University in 1990 with specialization in Energy and Process Technology.

Spezifikationen und wichtige Eigenschaften von Transformatorenölen im Hinblick auf eine optimale Einsatzdauer

Transformer oil specifications and important properties for optimal in-service life

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Nynas AB

Insulation oil used in transformer need to have chemical and physical properties in line with the basic functions it needs fulfilling. There are three main functions which transformer oil must handle in the transformer; to be an electric insulation barrier, to be a heat transfer medium and to preserve the transformer over time. To secure these basic functions there are specifications that have been developed over time, based on experience and demands from different parties on the market. The leading transformer standard specifications are IEC 60286 and ASTM D 3487. The requirements in the standards are defined with minimum and maximum limits. There are requirements on physical and chemical properties which depending on the base fluid and its degree of refining, but other properties like dielectric insulation needed for this application are also specified. Transformer oil can have properties that are just passing specification limits or can have properties which exceeding the requirements. The understanding of transformer oil qualities is important when deciding which oil is best for your equipment in order to get potential long in-service life.

Cooling and keeping the top oil temperature at a minimum in the transformer is a very important task for the fluid. This will minimize cellulose degradation and optimize in-service life for the transformer. Low viscosity at top oil temperature is the dominating property to achieve this in most transformer designs.

To insure a long in-service life for a transformer, the oil needs to have suitable oxidation stability for the application and loading pattern. Oxidation of the oil is driven by exposure to oxygen and heat generation mainly, but the oil oxidation resistance is deciding how much degradation there will be.

This paper shows the importance of knowledge about transformer oil properties to make an independent choice.

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What are the requirements on a Transformer Oil?

- Fulfill standards and specifications
- Last the lifetime of the transformer

- Act as electrical insulator
- Provide cooling
- Meet expected in-service behaviour

Spezifikationen und wichtige Eigenschaften von Transformatorenölen im Hinblick auf eine optimale Einsatzdauer

Fulfill standards and specifications

Specifications for unused oils

ASTM D3487 and **IEC 60296** are the most widely used International standards for insulating oil today

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Specifications for unused insulating oil

Insulating oil requirements

Classification according to inhibitor content

ASTM 3487;2000

Type I	Max 0.08 wt% inhibitor
Type II	Max 0.30 wt% inhibitor

IEC 60296;2003

Uninhibited	Natural inhibitors
Trace inhibited	Max 0.08 wt% inhibitor
Inhibited	Max 0.4 wt% inhibitor

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Specifications for unused oils

International standards	IEC 60296/03
	ASTM D3487
National specifications	CAN/CSA-C50-08 (Canada)
	AS 1767.1-1999 (Australia)
	JIS C 2320-1993 (Japan)
Equipment manufacturers	Siemens, Trench
Utilities and other bodies	ESKOM, TEIAS, Doble

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Spezifikationen und wichtige Eigenschaften von Transformatorenölen im Hinblick auf eine optimale Einsatzdauer

Summary of specified Transformer oil requirements

Cooling	Electrical insulation	Life time
Viscosity	Breakdown voltage	Oxidation stability
Pour point	Dielectric dissipation factor (DDF)	Inhibitor content
Viscosity index	Impulse breakdown	
	Resistivity	
	Water content	

Material compatibility	Health, safety and environment	Others
Sulphur content	Flash point	Density
Acidity	IP 346 (DMSO Extractable compounds)	Interfacial tension, IFT
Corrosive Sulphur		Furanic compounds
Aromatic content		Gassing tendency

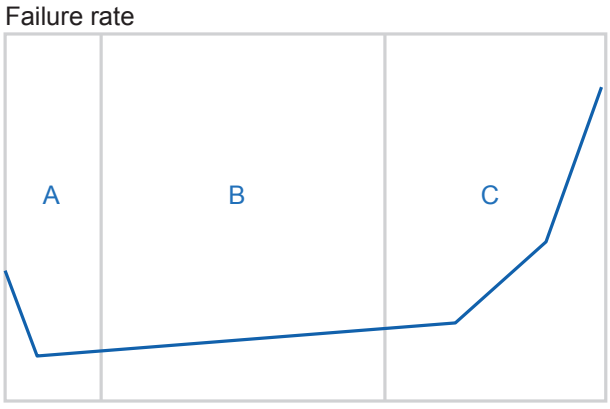
Last the lifetime of the transformer

Spezifikationen und wichtige Eigenschaften von Transformatorenölen im Hinblick auf eine optimale Einsatzdauer

What is the lifetime of a transformer dependent on?

- Design and materials
- Manufacturing and installation
- Operating conditions
- Ambient temperature
- Follow up and maintenance

Failure Rate vs Transformer Lifetime



A Running in Period
B Service Period
C Final Wear Phase

Study by Hartford Steam Boiler Inspection & Insurance Co. USA (2000)

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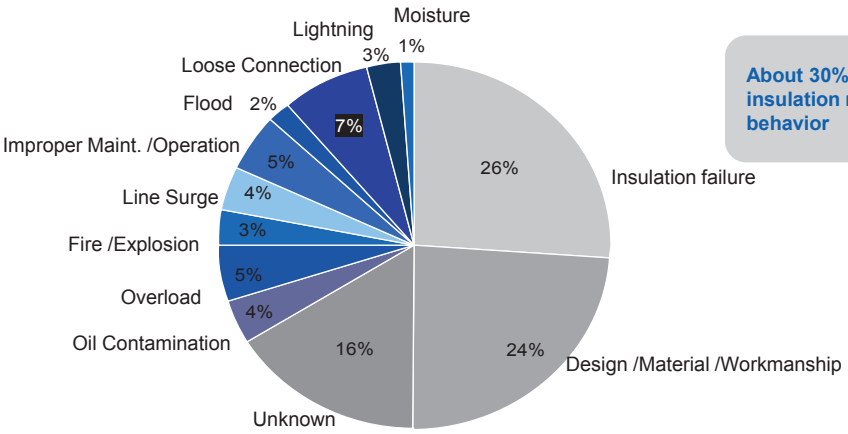
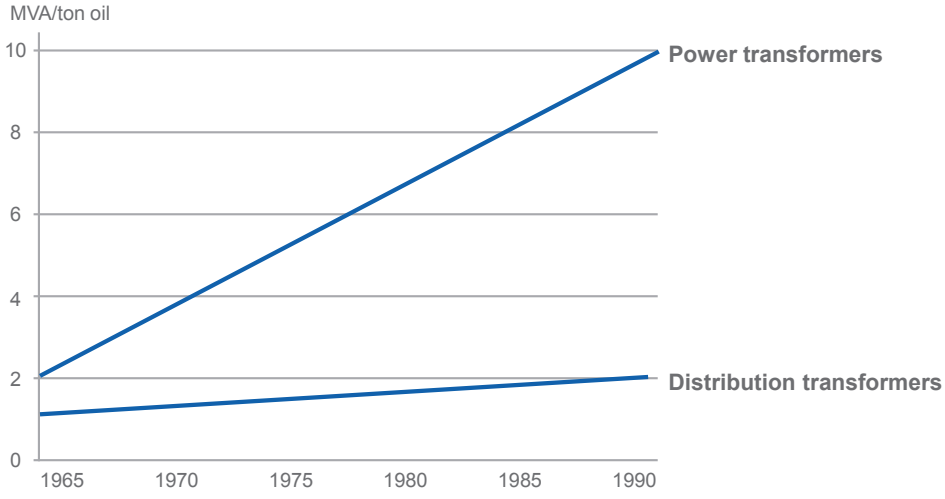
Cause of transformers failures



About 30% relates to insulation material behavior

Study by Hartford Steam Boiler Inspection & Insurance Co. USA (2003)

Development of the Power/Oil ratio of transformers



Indicated trend on the market to use less oil and have higher loads
→ higher demand on the oil!

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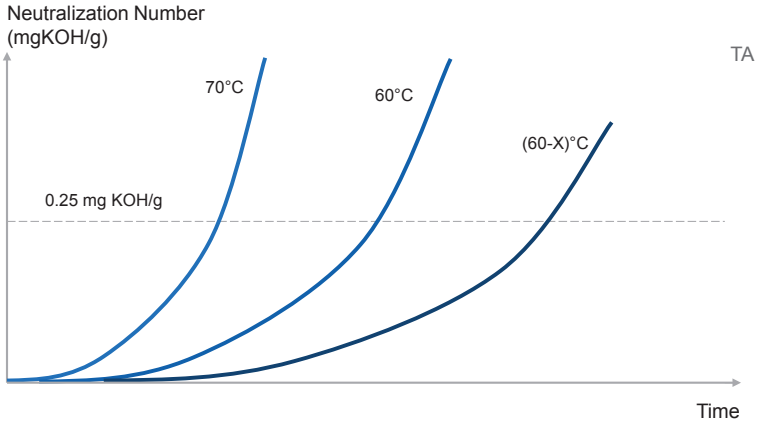
Transformer Oil Ageing vs Temperature

The rate of oxidation increases with temperature – hence the importance of cooling as this will extend the life of the transformer oil, and the transformer itself



IEC 60422
TA max : 0.50 mgKOH/g

Interaction between Paper and Oil

- Transformer oil is a replaceable product
  - Reclamation or replacement
- But the Kraft paper in a transformer is not replaceable

Life of Transformer = Life of the Paper

Spezifikationen und wichtige Eigenschaften von Transformatorenölen im Hinblick auf eine optimale Einsatzdauer

Values and benefits – Daily operations

Low pour point	Good flow properties at very low temperatures	
Excellent insulator	Can withstand very high electrical stress	Excellent compatibility with cellulose
Information carrier	Record & store fault gases	Allow to detect electrical & thermal faults

- Transformer can be energized in low temperatures
- Very strong and stable insulation system enable compact design and high voltages
- Diagnostic tool to prevent failures and avoid outages

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Values and benefits – Equipment lifetime

Low viscosity oils	Lower operating temperatures	Slow paper degradation
Good oxidation stability	Low acid values and low sludge production	Slow oil degradation
High solvency	Keep sludge dissolved in oil	Maintained cooling capacity

- Maintained dielectric properties
- Less maintenance over time
- Longer transformer life

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Spezifikationen und wichtige Eigenschaften von Transformatorenölen im Hinblick auf eine optimale Einsatzdauer

Act as electrical insulator

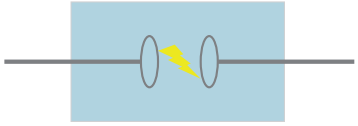
Breakdown Voltage

Transformer Oil as an Insulator

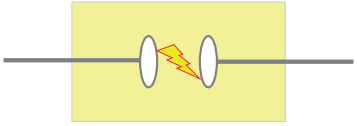
From insulation perspective, if correctly treated,
all mineral oils will meet requirements

BREAKDOWN VOLTAGE at room temperature

AIR: 10 – 15 kV



OIL: 50 – 90 kV



Distance between electrodes 2.5 mm

(Measurement: IEC 60156)

Spezifikationen und wichtige Eigenschaften von Transformatorenölen im Hinblick auf eine optimale Einsatzdauer

Dielectric strength oil & cellulose

12 + 40 = (52) 64

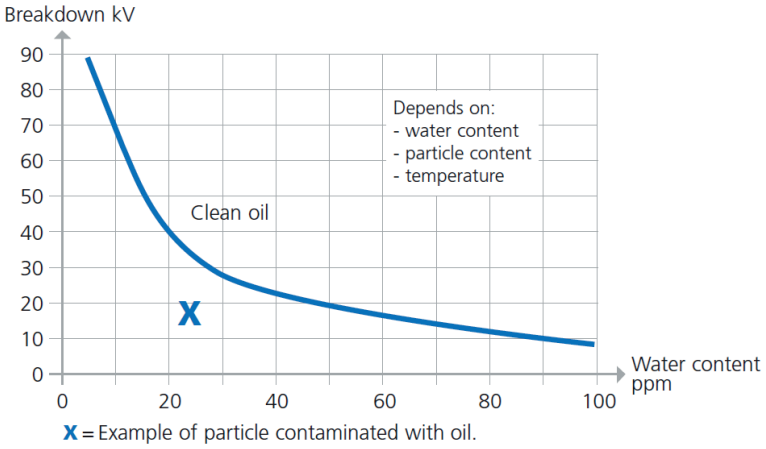
23% gain

Oil impregnated cellulose (kV/mm)

Cellulose (kV/mm)

Oil (kV/mm)

Dielectric breakdown vs water content at ambient temperature



Spezifikationen und wichtige Eigenschaften von Transformatorenölen im Hinblick auf eine optimale Einsatzdauer

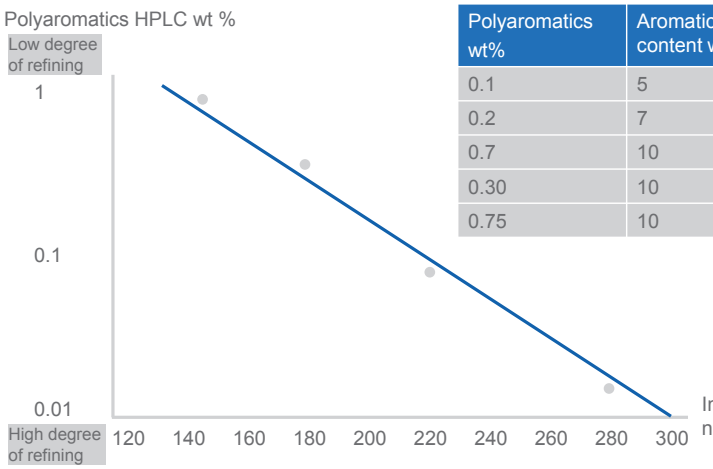
Act as electrical insulator
Impulse Breakdown

Impulse Breakdown

- The test is designed to simulate a lightning pulse striking a transformer
  - It measures the break down behavior with DC impulses
- **This property is effected by the degree of oil refining**
  - Could be seen as an oil quality measurement
  - It is not effected by contaminants in oil
- This property is usually not included in the specifications; exception ASTM D3487

Spezifikationen und wichtige Eigenschaften von Transformatorenölen im Hinblick auf eine optimale Einsatzdauer

Impulse Breakdown vs. Polyaromatics



Polyaromatics wt%	Aromatic content wt%	Impulse breakdown kV
0.1	5	>300
0.2	7	282
0.7	10	220
0.30	10	196
0.75	10	148

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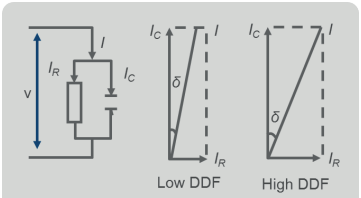
Act as electrical insulator

Dielectric Loss

Spezifikationen und wichtige Eigenschaften von Transformatorenölen im Hinblick auf eine optimale Einsatzdauer

Dielectric dissipation factor (DDF) and power factor

- DDF and power factor are two different ways to measure the same property (at low values these two will be more or less the same)
- It is a measure of the dielectric losses in oil and results in heat generation
- **This property depends on temperature and frequency of the AC-field, also impurities such as oxidation products and particles**
- The value should be as low as possible
- It is always included in specifications for unused oil



A non-ideal capacitor model
In an ideal capacitor I would equal I_C

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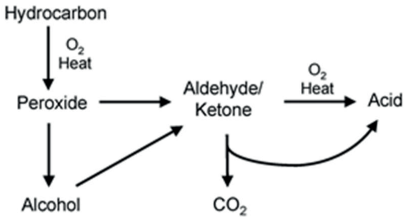
Meet expected in-service behaviour

Oxidation stability

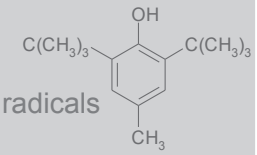
Spezifikationen und wichtige Eigenschaften von Transformatorenölen im Hinblick auf eine optimale Einsatzdauer

What is oil oxidation?

- In principle a very slow combustion
  - Oxygen + Fuel (oil) → Carbon dioxide + Water



- Inhibitors (antioxidants) hinders radical reactions
  - Good for transformer oil
  - Acts similar to vitamin C, "catches and disarms" radicals



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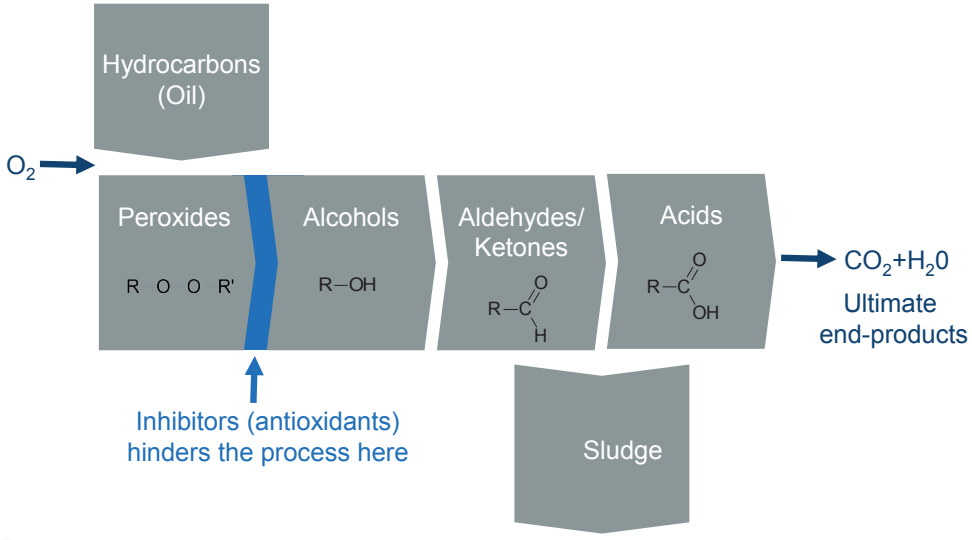
Principle of transformer oil oxidation



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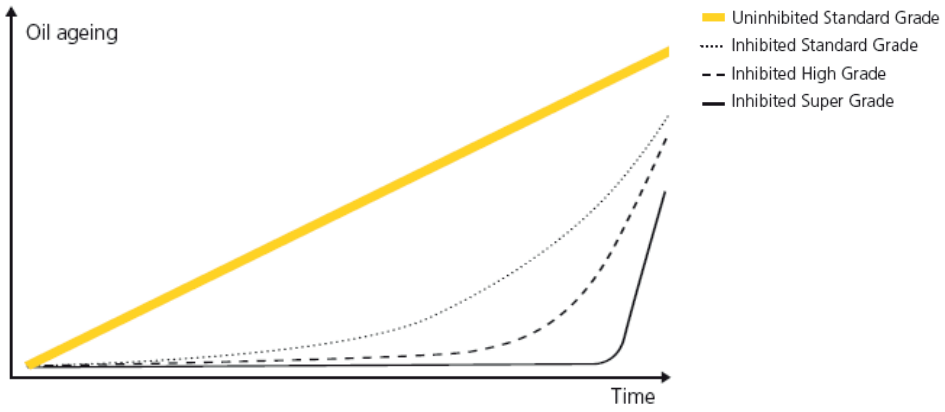
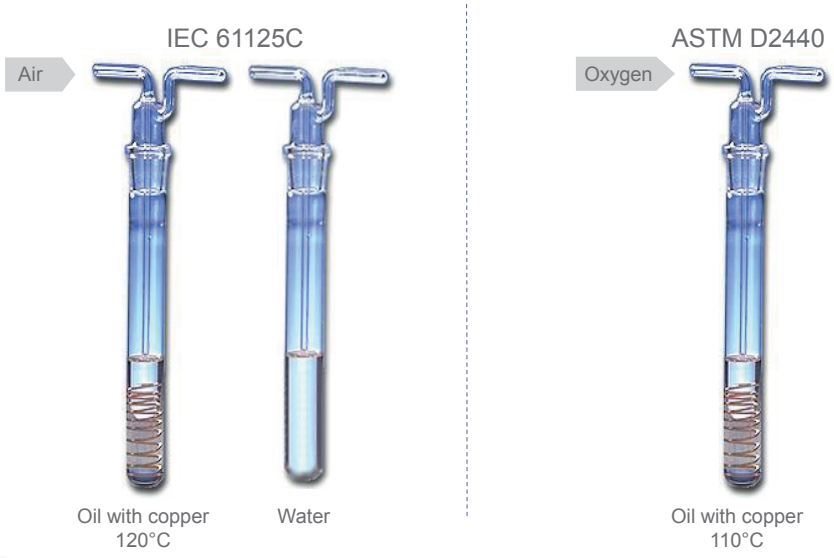
Spezifikationen und wichtige Eigenschaften von Transformatorenölen im Hinblick auf eine optimale Einsatzdauer

Oxidation behaviour – Inhibited vs Uninhibited oils

Oxidation behaviour of different types of oil



Oxidation Stability - test methods



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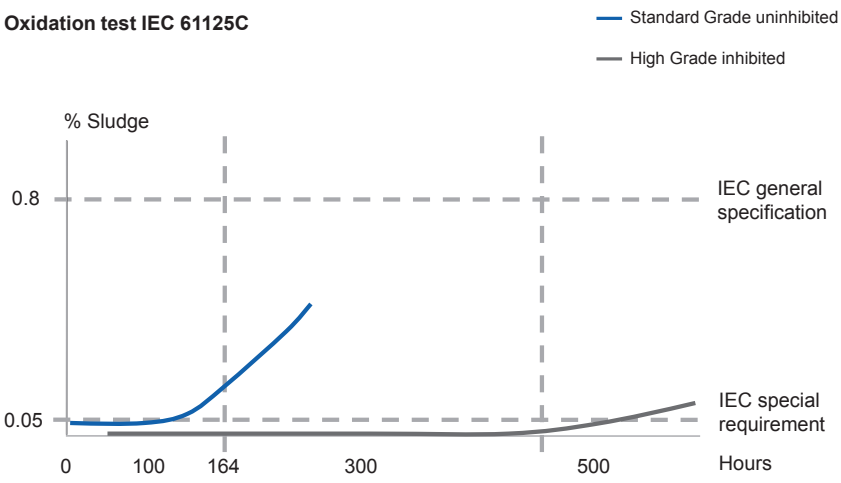
Oxidation behaviour of different insulating oils



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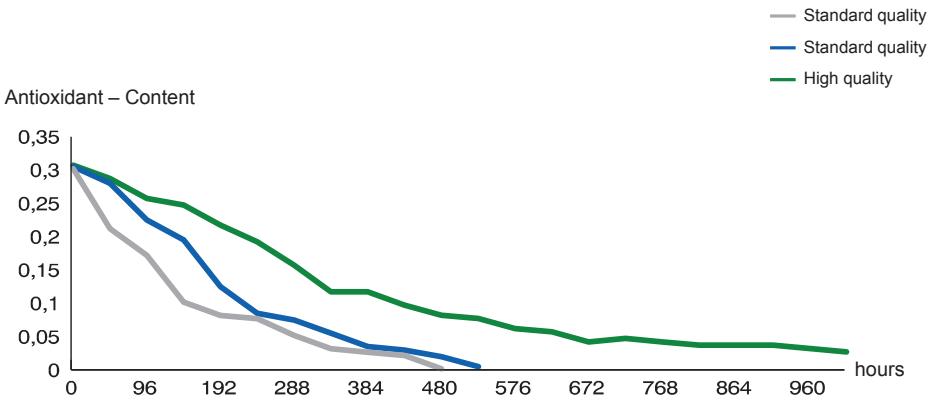
Consumption of Antioxidant Additive During Oxidation (IEC 61125C)



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Spezifikationen und wichtige Eigenschaften von Transformatorenölen im Hinblick auf eine optimale Einsatzdauer

Provide cooling
Energy losses

Energy Losses in Transformers

	Distribution transformer	Substation transformer	Generation EHV grid
Voltage	30 kV/400 – 220 V	110 kV/30 kV	400 kV/100 kV
Power	250 kVA	30 MVA	250 MVA
Oil volume	200 kg	7.5 MT	40 MT
Energy loss	5 kW	150kW	1.0 MW
Spec. loss per MT	25 kW/MT	20 kW/MT	25 kW/MT

Spezifikationen und wichtige Eigenschaften von Transformatorenölen im Hinblick auf eine optimale Einsatzdauer

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Provide cooling
Important oil properties for cooling

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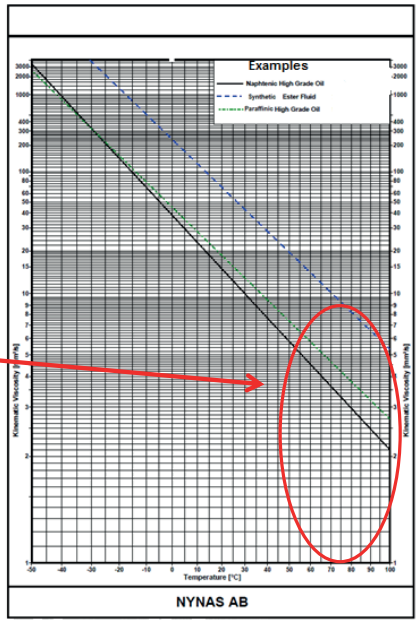
Viscosity and VI

This temperature zone is interesting for investigating cooling properties of oils



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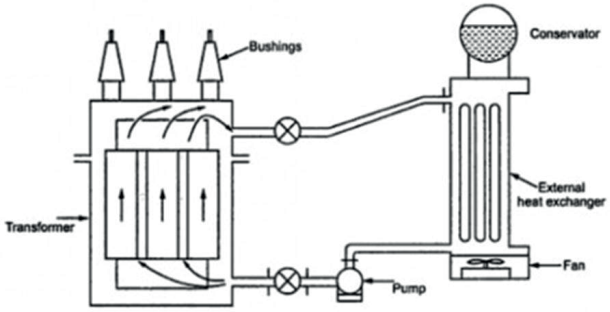
Oil forced cooling (OF)

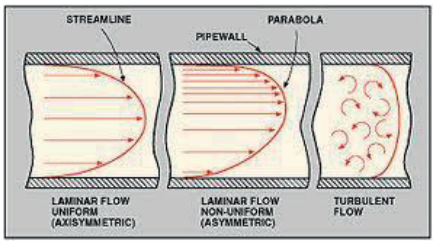


Flowing fluid and heat transfer in pipes

- At higher flow velocity the fluid will develop turbulence and this will be beneficial for the heat transfer.
- A lower viscosity increases heat transfer and turbulence

Turbulent flow

Laminar flow

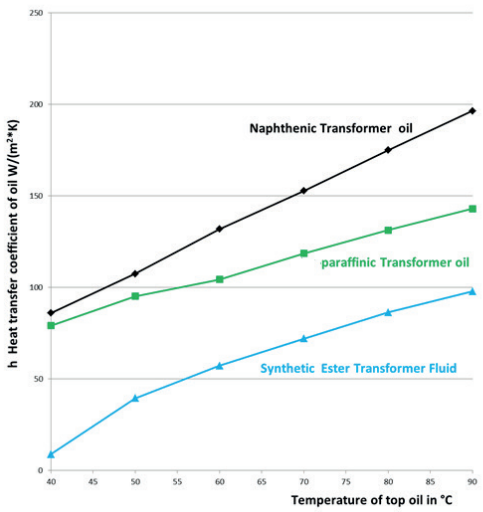


Spezifikationen und wichtige Eigenschaften von Transformatorenölen im Hinblick auf eine optimale Einsatzdauer

Calculations needed to evaluate heat transfer coefficent for a fluid

- Reynolds number : $Re_D = \frac{u*D}{\nu}$
  - Turbulent flow for Re over 2300
- Nusselt number: $Nu_D = \frac{h*D}{k}$
- For oil flowing in pipes, the following empiric correlation can be used;
- Gnielinski : $Nu_D = \frac{\frac{f}{8}*(Re-1000)*Pr}{1+12.7*\left(\frac{f}{8}\right)^{1/2}*(Pr^{2/3}-1)}$
  - Valid for $0.5 \leq Pr \leq 2000$
  - And $3000 < Re_D < 5*10^6$

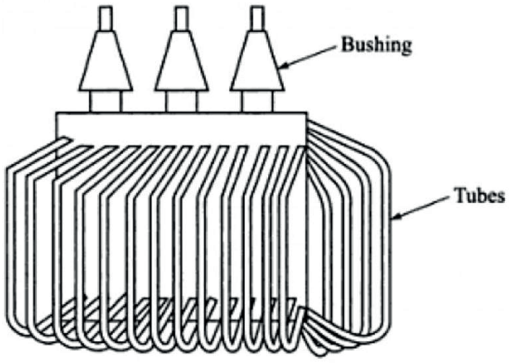
Heat transfer coefficient of three different types of transformer fluids



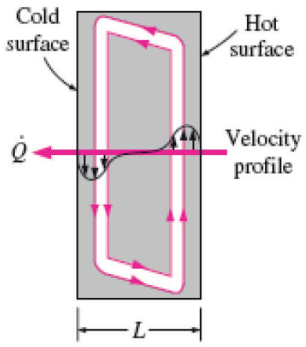
”A simplified cooler”:
Pipe Ø: 10 cm
Velocity: 0.5 m/s

Spezifikationen und wichtige Eigenschaften von Transformatorenölen im Hinblick auf eine optimale Einsatzdauer

Distribution transformers
Natural convection cooling (ON)



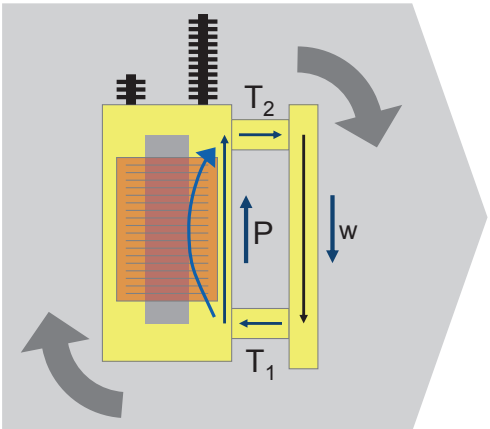
"Enclosed circulation"



$$\beta = \frac{1}{v}\left(\frac{\partial v}{\partial T}\right)_P = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_P$$

$$\rho_\infty - \rho = \rho * \beta * (T - T_\infty)$$

Free convection (ON)



$$w = f \cdot \frac{\Delta T}{v}$$

w = Flow Speed
f = Calculation Factor
ΔT = Temperature difference
ν = Kinematic Viscosity at Operation Temperature

Oil viscosity is the major parameter other than design that can influence the cooling!

Spezifikationen und wichtige Eigenschaften von Transformatorenölen im Hinblick auf eine optimale Einsatzdauer

Low Temperature Properties

Wax crystallisation at low temperatures prevents oil circulation and cooling which can cause damage to the transformer

Cold Start Properties

Transformer oils “Lowest cold start energizing temperature“ (LCSET defined in IEC 60296)

LC SET °C	Max Viscosity mm^2/s	Max Pour Point °C
0	1800	- 10
-20	1800	- 30
-30	1800	- 40
-40	2500	- 50

Spezifikationen und wichtige Eigenschaften von Transformatorenölen im Hinblick auf eine optimale Einsatzdauer

Summary

- Use the specification standards for un-used oil in IEC 60296 and ASTM D3487 as a guidance when purchasing insulation oil for transformers
- Use maintenace guides to keep the transformer (oil) in good condition, like Cigre 445 and IEC 60422

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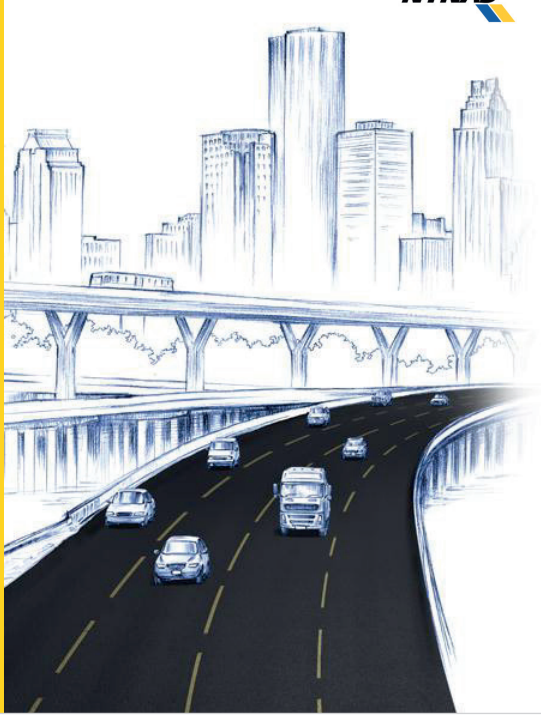

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