LIQUID INSULATION

ARC SUPPRESSION PROPERTIES

Switchgear using the arc suppression properties of insulating liquids (oils) was invented in the early 1880s. In the early days, the structure of switchgear was simple: a pair of electrodes were placed in insulating oil. In such switchgear the arc suppression mechanism is also simple: as the electrode spacing increases so the arc length increases and the electric arc is suppressed. This suppression results from the cooling effect of hydrogen gas produced by the decomposition of the insulating oil due to the arc. In arc suppression in insulating oil, hydrogen gas produced by decomposition of the insulating oil due to the arc plays an important role.

Arc Suppression by Hydrogen

The energy of the arc between a pair of electrodes in the insulating oil is dissipated by the electrodes, by conduction and radiation, evaporation and decomposition of the insulating oil, heating and expansion of gases produced by the decomposition of the insulating oil, and dissociation of hydrogen. Fifty to seventy percent of produced gas is hydrogen, and the other gases are acetylene, methane, and ethane. As shown in Table 1, the thermal conductivity of hydrogen at room temperature is higher than that of other gases. At 4000°C it is about 50 W/m · K. This value is more than 5 times higher than for the other gases. Therefore, the cooling effect is larger than that of the other gases. By this cooling, the arc is suppressed at the zero-current point of alternating current. Thus the current is

Table 1. Heat Conductivity of Gases

Gas	Heat conductivity (W/m · K)
Hydrogen	0.175
Methane	0.031
Ethane	0.018
Acetylene	0.017

cut off. Switches that utilize this arc suppression mechanism are called plane-break oil circuit breakers.

As the current increases, it becomes more difficult to suppress the arc. Therefore, the breaking time (cutoff) of the current becomes longer. However, when the current exceeds a certain magnitude, a large amount of hydrogen—enough to suppress the arc—has been produced. At this point the breaking time is again reduced. This means that the breaking time shows a maximum value at a certain magnitude of current.

Arc Suppression by an Explosion Chamber

Cooling may not be sufficient to suppress a high-current arc and to lessen the breaking time. In this case explosion chambers are used. In a simple explosion chamber a movable electrode of the circuit breaker (switchgear) acts as a stopper of the chamber. In the early stages of separating the electrode, the arc is enclosed in the limited space of the chamber. Therefore, the pressure in the chamber rises owing to gases produced by decomposition of the insulating oil. As this process proceeds, the stopper is removed creating an exhaust hole.

Through this exhaust hole the gases in the chamber are released abruptly. By this release, flows of gases and oil are produced, and the arc is pressurized and blasted. These processes create efficient arc suppression. Furthermore, when the lengthened arc contacts insulating solids while enclosed in narrow gaps between them, more efficient arc suppression results.

Because gases are abruptly exhausted through the hole, adiabatic expansion occurs. Thus cooling is expected. In some oil circuit breakers this is the main effect utilized. Some scientists maintain that in oil circuit breakers with an explosion chamber, arc suppression can be entirely explained by the cooling effect owing to the adiabatic expansion. In fact, however, insulating oils exhibit not only the arc suppression property resulting from the cooling effect of hydrogen, but also the substantially different suppression properties of the oils themselves. In high-current arc suppression, these two types of suppression properties are combined.

In circuit breakers with an explosion chamber, a large pressure rise is expected in the chamber in the case of high-current arc suppression, but not in the case of low-current suppression. Thus in the latter case the breaking time is longer, because the arc must be suppressed by the cooling effect of hydrogen alone. Therefore, the breaking time shows a maximum at a certain magnitude of current (the critical current). But this breaking time is much shorter than that of the plain-break oil circuit breaker. A circuit breaker with an explosion chamber necessarily has plural arc suppression mechanisms.

In some circuit breakers, in the region of the critical current, the auxiliary flow of the oil is forced by a piston to supplement the pressure rise and the conduction cooling effect. By this means a constant breaking time is obtained over a wide range of current.

Plane-break oil circuit breakers are used for low voltages and low currents, such as 3.6 kV to 7.2 kV and 4 kA to 8 kA. Oil circuit breakers with an explosion chamber are used for high voltages and high currents. In the case of multibreak circuit breakers, 700 kV with currents of several tens of kiloamperes have been achieved (1).

DISCHARGE RESISTANCE

The behavior of insulating liquids under highly stressed conditions and under conditions of partial discharge are among the most important items in screening tests for newly developed insulating liquids and also in the routine testing of liquids.

Gassing Rate

Methods of evaluating gas absorption and evolution of insulating oils under high stress after saturation with a gas are described in IEC 628 and ASTM D 2330. The fundamental approaches are similar to each other and amount to a modified Pirelli method.

The condition used in such methods differs from actual field conditions, especially in the case of hermetically sealed equipment such as power cables, capacitors, and many power transformers.

Discharge Resistance

To evaluate the behavior of insulating liquids in a highly stressed impregnated system and to obtain numerical results for the recently developed impregnants with very high resistance to partial discharge, the above-mentioned methods are not sufficient. As new liquids, especially with high aromaticity, are developed and applied voltage stresses are progressively increased, a new method is needed to characterize the ability of such insulating liquids to prevent or suppress partial discharge under high stress. One of these methods, determination of the partial discharge inception voltage with a needle and spherical ball oil gap, is described in IEC 61294. The partial discharge inception voltage obtained by this method is largely related to the chemical structure of the liquid and is correlative to partial discharge in impregnated insulating systems such as capacitor elements.

DIELECTRIC CONSTANT AND LOSS

Dielectric polarization occurs when an electric field is applied to insulating oil. When there is a time delay in the formation of polarization, dielectric loss arises from the phase delay of polarization under an alternating electric field. The loss due to this dielectric polarization is proportional to the dielectric loss tangent tan δ, which is equal to the ratio of the dielectric loss factor ϵ'' to the dielectric constant ϵ':

$$\tan\delta = \epsilon''/\epsilon' \qquad (1)$$

The temperature dependence of tan δ and ϵ' in three mineral insulating oils is shown in Fig. 1. At a frequency of 1 kHz, the maximum of tan δ is observed at $-40°$C to $-50°$C. The maximum value moves to higher temperatures as the measurement frequency is increased.

The maxima in tan δ and in the dielectric loss factor ϵ'' are caused by asymmetry of the molecular structure leading to dipole moments in, for example, aromatic compounds. These maximum values increase as the insulating oil deteriorates.

The frequency f_m (Hz) at which tan δ or ϵ'' are a maximum has the following temperature dependence:
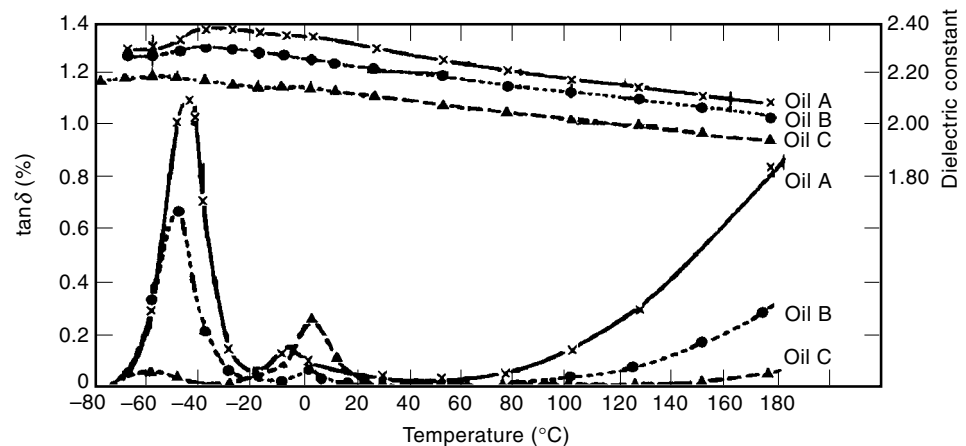
$$f_m = f_0\exp(-\Delta H/RT) \qquad (2)$$

Figure 1. Temperature dependence of dielectric constant and tan δ at 1 kHz in mineral insulating oil.

where f_0 is a constant (Hz), ΔH is the activation energy (cal/mol), R is 1.987 cal/mole·K, and T is the absolute temperature (K). The value of ΔH is about 20 kcal/mol for insulating oil with 15% of aromatic compounds, and about 40 kcal/mol for insulating oil without aromatic compounds.

Equation (2) applies over a rather narrow temperature range. On the other hand, it is known that the following equation, due to Williams, Landel, and Ferry (WLF), applies over a wider temperature range:

$$\ln \frac{f_{m0}}{f_m} = \frac{C_1(T - T_0)}{C_2 + (T - T_0)} \tag{3}$$

where f_{m0} is the frequency that yields the maximum value of tan δ at temperature T_0, f_m is the frequency that yields the maximum value of tan δ at temperature T, and C_1 and C_2 are the WLF constants. ΔH is expressed by the following equation, deduced from Eqs. (2) and (3):

$$\Delta H = \frac{2.303 R C_1 C_2 T^2}{C_2 + T - T_0} \tag{4}$$

which applies over a wide temperature range. C_1 and C_2 are obtained from the slope and intercept of $1/\ln(f_{m0}/f_m)$ plotted against $T - T_0$, in view of Eq. (2).

There is no effect due to the orientation of dipoles above room temperature at low frequencies, such as those of commercial power. However, the mobility of the charge carriers is high, and electric conduction losses can be large. The electric conduction loss is caused by the conduction due to ions that arise for impurities and from the dissociation of the insulating oil itself. Therefore, tan δ can be related to the volume resistivity ρ that is obtained from dc measurements:

$$\tan \delta = 100/\omega \epsilon' \epsilon_0 \rho \tag{5}$$

where tan δ is in percent, ω ($=2\pi f$, where f is the frequency of the voltage) is the angular frequency, ϵ' is the dielectric constant, ϵ_0 is 8.85×10^{-14} F/cm, and ρ is in ohm-centimeters.

Dissipative current is observed on applying a dc voltage to the electrode that measures the volume resistivity of the insulating oil. The volume resistivity ρ in Eq. (5) is calculated from the current i_0 that is obtained at time $t = 0$.

In recent years, a measuring device that can read tan δ directly has been marketed. In its absence, however, tan δ can be calculated from Eq. (5).

Values of the dielectric constant and tan δ of various insulating oils are shown in Table 2.

THERMAL TRANSFER CHARACTERISTICS

Cooling Method

Insulating liquids (oils) have not only excellent dielectric characteristics but also significant cooling effects. Insulating oils are important coolants in apparatus in which much heat is produced. Nevertheless, external cooling systems must sometimes be added, depending on the capacity of the apparatus and the load.

In the case of transformers, there are several types with different cooling methods, such as the oil-immersed self-cooled type, forced-oil self-cooled type, direct-oil-flow self-cooled type, forced-oil forced-air-cooled type, direct-oil-flow forced-air-cooled type, oil-immersed forced-water-cooled type, and forced-oil forced-water-cooled type. Oil-immersed self-cooling is the simplest method. In this method transformers are cooled by natural convection. In other methods heated insulating oils are cooled by forced air, forced oil, or water using coolers or heat exchangers. In high-voltage and high-power transformers the latter methods are widely used.

Table 2. Dielectric Constant and tan δ in Various Insulating Oils[a]

Insulating Oil	Dielectric Constant	tan δ (%)
Mineral oil	2.18	0.02
5-Chlorobiphenyl	4.25	0.03
3-Chlorobiphenyl	5.20	0.04
Chloroalkylene	5.05	<0.01
Trixylenyl phosphate	6.00	1.0
Diethylhexylphthalate	4.55	0.10
Castor oil	4.00	0.30
Alkylbenzene	2.17	0.005
Alkyl naphthalene	2.48	0.01
Alkylbiphenylethane	2.51	0.10
Silicone oil	2.52	0.008

[a] 60 Hz 80°C.

Heat Transfer Characteristics of Insulating Oils

When insulating oil cools insulating solids that cover a heat source, such as the paper on transformer windings, the heat flux through the solid to the oil is expressed in (2)

$$q = KS(T_1 - T_2) \tag{6}$$

$$K = \frac{1}{\dfrac{1}{\alpha} + A\dfrac{d}{\lambda}} \tag{7}$$

where

q = heat flux through solid to oil
K = overall heat transfer coefficient
S = area of solid that is in contact with oil
T_1, T_2 = temperatures of heat source and oil respectively
α = heat transfer coefficient
A = constant
d = thickness of solid
λ = heat conductivity of solid (insulating material)

The larger q is, the more effective the cooling. The amount of heat flux is controlled by K, and thus by α. The magnitude of α depends on physical properties of the insulating oil, and the structure of the insulating material. The important physical properties of the oil are the density, kinetic viscosity, thermal expansion coefficient, heat conductivity, and velocity.

The heat flux is also expressed by

$$q = \alpha S(T_m - T_2) \tag{8}$$

where

T_m = temperature of insulating material

α is generally obtained from the Nusselt number Nu by

$$Nu = \alpha \frac{l}{\kappa} \tag{9}$$

The Nusselt number is a function of the Reynolds number Re, the Grashof number Gr, the Prandtl number Pr, the temperature difference between the insulating material and the oil, and the thickness of the insulating material:

$$Re = v\frac{l}{\nu^2} \tag{10}$$

$$Gr = \frac{g\beta^3(T_m - T_2)}{\nu^2} \tag{11}$$

$$Pr = \frac{\nu}{a} \tag{12}$$

where

l = length of insulating materials
κ = heat conductivity of insulating oil
v = velocity of insulating oil
ν = kinematic viscosity of insulating oil
g = acceleration of gravity
β = thermal expansion coefficient of insulating oil
a = thermal diffusivity of insulating oil

In the expression for Nu, Re always appears in the form Re^n ($n > 0$). Therefore, generally speaking, the higher the velocity is, the higher is α. For instance, in the case of a flat plane exposed to forced convection of liquid, Nu is expressed by

$$Nu = \text{const} \times Pr^{1/3}Re^{1/2} \tag{13}$$

The cooling characteristics of a duct model of transformers with a sufficiently large reservoir of insulating oil have been investigated for the case that the oil flow is laminar (3). The average temperature of a winding, Ta, is expressed by

$$T_a - T_i = \Delta T + \phi \tag{14}$$

where

$$\Delta T = 1.22 \left(\frac{10^{-6} \times WH\nu}{g\beta\rho Cd^3} \right)^{1/2} \tag{15}$$

$$\phi = 0.858 \left(\frac{10^{-6} \times W^7 H d^3 \nu}{g\beta\rho C\kappa^6} \right)^{1/8} \tag{16}$$

where

T_i = temperature of insulating oil at inlet of duct
ϕ = temperature rise of winding above average temperature of insulating oil
ΔT = average temperature rise of insulating oil in duct
W = thermal loading into duct (W/m²)
H = height of duct (m)
d = half the duct depth (m)
C = specific heat of insulating oil (W · s/kg)
ρ = density of insulating oil

As shown in Eq. (15) and Eq. (16), it is desirable for cooling that the kinematic viscosity be low and that the thermal expansion coefficient, density, specific heat, and thermal conductivity be high.

In Table 3 physical properties of some mineral oils, silicone liquids, and high-molecular-weight hydrocarbon oils are shown. Using these data, ΔT and ϕ of three oils were calculated. Ratios of ΔT and ϕ of silicone liquids and high-molecular-weight hydrocarbon oils to those of mineral oils are shown in Table 4. The physical properties of the three oils are not very different, except for the kinematic viscosity. The high kinematic viscosity reduces heat transfer, as in the case of silicone and high-molecular-weight hydrocarbon oils.

RESISTANCE TO IGNITION

Because of increasing environmental problems due to the bioaccumulative nature of polychlorinated biphenyls (PCBs), the production and use of PCBs have been prohibited throughout the world. Almost all substitutes for PCBs are more flammable than the PCBs, and the evaluation of flammability of those liquids becomes very important.

There are many test methods for the evaluation of the resistance to ignition and fire propagation of insulating liquids.

Table 3. Physical Properties of Insulating Oils

Property	Naphthenic Oil	Paraffinic Oil	Silicone Liquid	High-Molecular-Weight Hydrocarbon
Heat conductivity (W/m · K)				
25°C	0.120	0.132	0.136	0.134
100°C	0.109	0.116	0.128	0.119
Specific heat (kJ/kg · K)				
25°C	2.05	1.96	1.49	1.63
100°C	2.33	2.33	1.65	1.90
Density [kg/(0.1 m)^3]				
25°C	0.87	0.86	0.96	0.88
Thermal expansion coefficient (K^{-1}):				
25°C	7.8×10^{-4}	7.8×10^{-4}	1.04×10^{-4}	8.0×10^{-4}
Kinematic viscosity (m^2/s)				
25°C	11×10^{-6}	12×10^{-6}	50×10^{-6}	350×10^{-6}
100°C	2.1×10^{-6}	2.2×10^{-6}	16×10^{-6}	16×10^{-6}

Flash Point and Fire Point

Determination of the flash and fire points of petroleum products by the Cleveland open cup method is described in ISO 2592, and that of the flash points of petroleum products and lubricants by the Pensky–Martens closed cup method is described in ISO 2719. These are normative and very easy methods, now being used worldwide and specified by various standards for the evaluation of flammability of insulation liquids of almost all types.

Oxygen Index

Determination of the oxygen index of insulating liquids is described in IEC 61144. This method is an adaptation for liquids of ISO 4589, which has the same principles and is applicable to solids. The oxygen index is defined as the minimum concentration of oxygen by percentage volume in a mixture of oxygen and nitrogen that will just support combustion of a material. The smaller the index, the more combustible a tested liquid is.

Net Calorific Value

Determination of the net calorific value or net heat of combustion of liquid hydrocarbons with a bomb calorimeter described in ASTM D 240 is specified in ISO 1928. This quantity represents the rate of heat generation by the liquid during its combustion.

Other Fire Tests

The pool fire test (large scale and small scale), trough test, spray mist test, and heat release test, developed by Factory Mutual Research, are attractive and practical methods to evaluate the ease of ignition and behavior of liquids during combustion, but the required equipment is bulky and requires ample space.
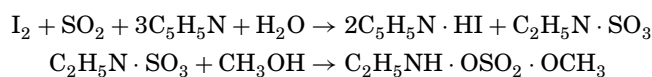
Linear Flame Propagation Test

The linear flame propagation test method, using a glass fiber tape, is described in IEC 61197. A glass fiber tape impregnated with the sample liquid is ignited at one end, and the time for the flame to travel between two lines is measured. This method is very easy to set up and useful for impregnated systems.

The method to be selected for the evaluation of fire hazard depends on the kind of machine and conditions of use. No single method is always effective, and in many cases some combination of the methods mentioned above is necessary. For example, classification of insulating liquids according to fire point and net calorific value is given in IEC 61100.

MOISTURE EFFECT

Moisture in Insulating Oil

Moisture in insulating oil leads to a decrease of volume resistivity and to dielectric breakdown. The moisture content is related to the humidity in the atmosphere and also changes with the oil temperature. Standards for it are given in JIS C 2101, BS 2511, IEC Publ. 733, and also ASTM D 1533. One method of measuring it uses Karl Fischer's reagent, which reacts sensitively with very small quantities of moisture. The reactions between Karl Fischer's reagent and water are as follows:

$$I_2 + SO_2 + 3C_5H_5N + H_2O \rightarrow 2C_5H_5N \cdot HI + C_2H_5N \cdot SO_3$$
$$C_2H_5N \cdot SO_3 + CH_3OH \rightarrow C_2H_5NH \cdot OSO_2 \cdot OCH_3$$

A liquid mixture of chloroform and methanol is used for the titration solvent.

Dissolved water content in liquids in general is determined by the relative humidity and the temperature of the atmo-

Table 4. Ratios of ΔT and ϕ of Silicone Liquids and High-Molecular-Weight Hydrocarbon Oils to Those of Mineral Oils[a]

Property	Mineral Oil	Silicone Liquid	High-Molecular-Weight Hydrocarbon
ΔT	1.00	2.75	2.99
ϕ	1.00	1.18	1.26

[a] Except for the density and thermal expansion coefficient, characteristics at 100°C were used for the calculations.

sphere. The relation is expressed by Henry's law,

$$X = X_{max}\psi = KP_W \qquad (17)$$

$$K = \frac{X_{max}}{P_{Wsat}} \qquad (18)$$

where X is the moisture density (mol %), X_{max} is the largest possible dissolved water content (mol %), ψ is the relative humidity (%) of the atmosphere, P_W is the vapor pressure, and K is Henry's constant, and P_{Wsat} is the saturated vapor pressure. Figure 2 shows the relation between dissolved water content in the insulating oil and the relative humidity of the atmosphere at various temperatures. Generally for synthetic oils the dissolved water content is larger because their hydrophilic nature is stronger than that of mineral oil.

When moist insulating oil is cooled, the dissolved moisture becomes supersaturated at a certain temperature and turns to white mud. The dielectric breakdown voltage decreases sharply when that happens. The usefulness of the insulating oil depends both on the degree of saturation and on the absolute moisture content.

Moisture in the Insulating Oil and Dielectric Breakdown Voltage

Moisture in the insulating oil not only decreases the dielectric breakdown voltage and volume resistivity, but also corrodes metals and degrades the insulating oil. Moisture in the insulating oil can be due to oxidative deterioration of the oil itself as well as to hygroscopic absorption from the atmosphere.

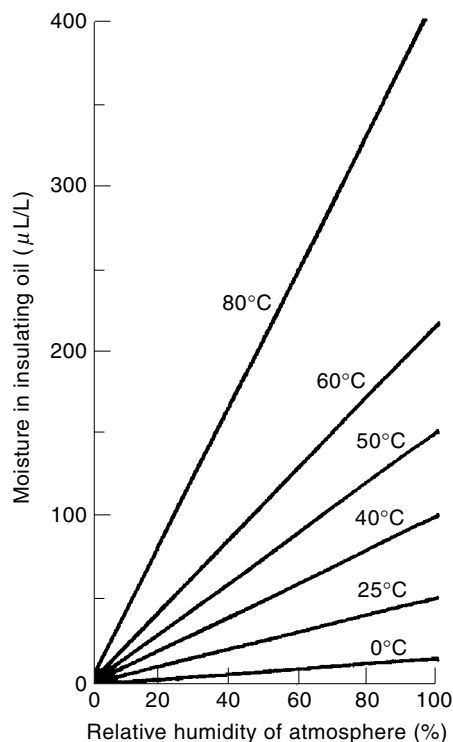The temperature dependence of the dielectric breakdown voltage in transformer oil, alkylbenzen, and PCBs is de-

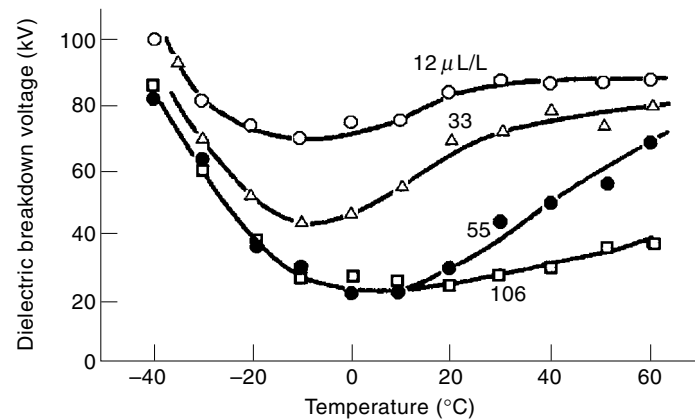**Figure 2.** Relation between moisture in insulating oil and relative humidity of atmosphere.

Figure 3. Temperature dependence of dielectric breakdown voltage in transformer oil. ○ = Nitrogen sealed-off transformer; ● = transformer with rubber-bag conservator.

scribed by a U-shaped curve with a minimum at −10°C to 0°C (4). The dependence for transformer oil is shown in Fig. 3.

For 30 μL/L moisture in insulating oil, the white mud temperature is the same as the temperature at which the dielectric breakdown voltage shows a minimum value. The dielectric breakdown voltage at ordinary temperatures decreases with increasing water content in the oil up to about 100 μL/L, and is essentially constant for greater water content.

Although fiber and dust in dehydrated oil decrease the dielectric breakdown voltage to some extent, in hygroscopic oil they decrease it dramatically.

AGING EFFECTS

Oxidation Stability of Insulating Oil

The insulating oil reacts with oxygen and generates organic acids, sludge, water, and other matter. These contaminants significantly degrade the electrical characteristics of the insulating oil. The organic acid and the moisture advance corrosion and other deterioration of materials in contact with the oil, and sludge lowers its cooling efficiency. Therefore, oxidation stability of the insulating oil is important for the life and reliability of oil-filled electrical equipment. It is known that the copper used for conductors in electrical equipment can catalyze the oxidative deterioration of the insulating oil (5,6).

The oxidation stability of the insulating oil is evaluated from the amount of sludge, total acid number, and electrical characteristics after heating the insulating oil in contact with excess oxygen and copper. Test methods are described in IEC Publications 74, 474, 813; ASTM D 1313, 1934, 2112, 2440; BS 148; DIN 51554; and JIS C 2101. Tests are carried out at 100°C to 120°C. Since ASTM D 1313 uses no catalyst, that test is done at the highest temperature (140°C).

The oxidation stability of mineral oil is influenced by its degree of refinement. However, higher refinement does not necessarily mean higher stability. Research on improved oxidation stability of insulating oil is often done from the viewpoint of optimum aromaticity.

tan δ of Insulating Oil in Relation to Oxidative Deterioration

The insulating oil of oil-immersed electrical devices that are equipped with oxidation deterioration prevention devices does
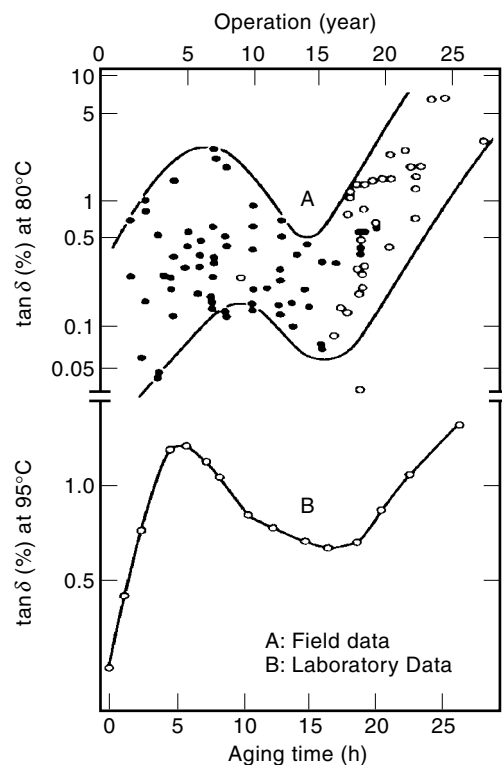
Figure 4. tan δ behavior for actual transformer oil in the field (A) and insulating oil in laboratory data (B).

not come in direct contact with the atmosphere. Therefore the oxidative deterioration of the insulating oil is slow. As shown in Fig. 4, the temperature dependence of tan δ for insulating oil shows peculiar behavior.

In Fig. 4, the band marked A shows the deterioration of tan δ in the insulating oil in a nitrogen-enclosed transformer and in a sealed transformer, at 80°C, gathered from many transformers over years of operation. The time dependence of tan δ yields an N-shaped curve. A peak is observed at 5 to 7 years after the start of operation. This behavior is confirmed in laboratory experiments. It implies that oxygen and copper play an important role.

Curve B shows laboratory data on the deterioration of insulating oil where the copper surface area was 44.8 cm^2 per 100 mL of oil, the oxygen volume was 5 mL per 100 mL of oil, and the oil temperature was 95°C (7).

From comparison of curves A and B, one hour of deterioration as accelerated in the laboratory is seen to be equivalent to about one year in operation.

FLOW-INDUCED ELECTRIFICATION

Insulating oil, like petroleum system liquids such as gasoline, toluene, and kerosene, has high volume resistivity. In such insulating liquids, ionic compounds A^+B^- dissociate into A^+ and B^-, and the ions become charge carriers:

$$A^+B^- \rightarrow A^+ + B^-$$
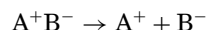
There is no charging when the numbers of A^+ and B^- are equal. However, for example, static electrification is observed

when the number of positive ions is increased by the flow of liquid. This static electrification is called *streaming electrification.*

Mechanisms of Streaming Electrification

The streaming electrification process arises from electric charge motion, separation, and relaxation (Fig. 5). These processes happen simultaneously:

1. *Electric Charge Motion.* Certain ions in the liquid are adsorbed on a solid in contact with it.
2. *Electric Charge Separation.* Other ions are carried off by flow, and an imbalance of positive and negative ions occurs.
3. *Electric Charge Relaxation.* Surplus ions are neutralized, and the imbalance is canceled.

Properties of Streaming Electrification

When the following three conditions coexist, large streaming electrification is observed:

1. It is easy to move an electric charge, because a solid surface is active.
2. Charges are easily separated.
3. Surplus electric charge is not easily canceled.

When any one of the three processes is hindered, streaming electrification can be prevented. The choice of insulating oil can also affect streaming electrification.
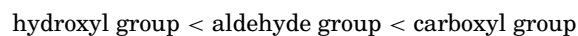
Polarity of Streaming Electrification

In streaming electrification between insulating paper and insulating oil, the oil becomes positively charged and the insulating paper negatively charged. A possible reason is a peculiarity of the oxygen of the hydroxyl group (–OH) in the insulating paper (cellulose).

Oxygen, having high electronegativity (that is, ability to attract electrons), attracts the electron of hydrogen. It thereby becomes negatively charged, and the hydrogen becomes positively charged. The cellulose molecule surface is covered with positively charged hydrogen, which adsorbs negative ions in oil selectively. Therefore, the insulating oil becomes positively charged, and the insulating paper is negatively charged.

Streaming Electrification and the Deterioration of Insulating Paper

The hydroxyl group (–OH) of cellulose is changed to the aldehyde group (–CHO) or the carboxyl group (–COOH) by oxidative deterioration. The extent of polarization due to electron transfer from hydrogen to oxygen, mentioned above, is in the following order:

hydroxyl group < aldehyde group < carboxyl group

Accordingly, streaming electrification increases as the insulating paper deteriorates.

Streaming Electrification of Transformers

Streaming electrification became a problem for the first time with large-capacity transformers (8). Accidents (9,10) due to
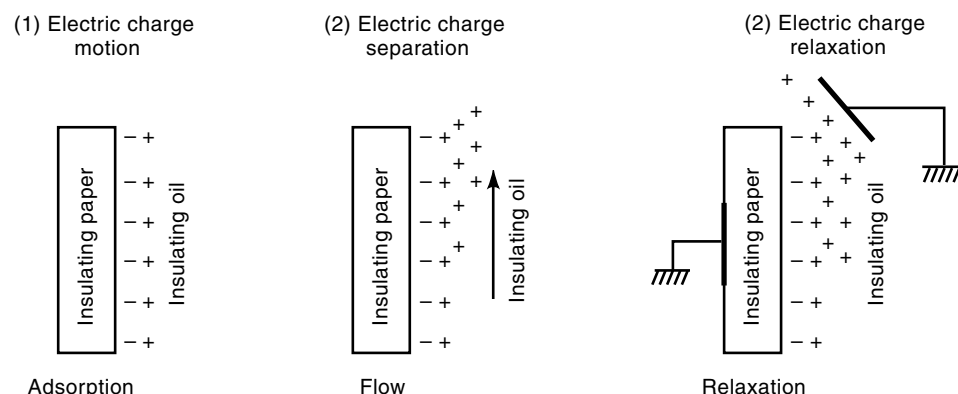
(1) Electric charge motion

(2) Electric charge separation

(2) Electric charge relaxation

Adsorption

Flow

Relaxation

Figure 5. Sketch of the mechanisms of streaming electrification.

streaming electrification, and also direct observation of streaming electrification (9) in transformers have been reported. A good measure of the streaming electrification in a transformer is the coil leakage current.

Figure 6 shows the oil temperature dependence of the coil leakage current, and reveals that it is influenced by differences in the insulating oil.

Coil leakage current is significant at all operating temperatures in large-capacity transformers. Therefore, measurement of the streaming electrification is essential in transformer design with respect to internal structure, oil flow rate, and insulating material. One may also select an oil that resists charging and charge separation.

MINERAL OILS

Crude Oils

Mineral insulating oils have a long history and have been used for transformers, cables, capacitors, and circuit breakers. They are manufactured by refining crude oils. The main compounds in crude oils are naphthenic hydrocarbons, paraffinic hydrocarbons, and aromatic hydrocarbons. Small amounts of sulfur compounds, nitrogen compounds, and oxygen compounds also occur. The naphthenic hydrocarbons include dicyclic, tricyclic, and alkyl-substituted hydrocarbons; the paraffinic hydrocarbons include normal paraffinic and isoparaffinic hydrocarbons; and the aromatic hydrocarbons include dicyclic, tricyclic, and alkyl-substituted hydrocarbons.

The composition of crude oils depends on the area where they are produced. There are three kinds of crude oils: naphthenic, paraffinic, and mixed. Naphthenic crude oils contain a large amount of naphthenic hydrocarbons, and paraffinic crude oils contain a large amount of paraffinic hydrocarbons. Mixed crude oils are intermediate between naphthenic and paraffinic. Naphthenic crude oils are produced in South America, North America, and southern Asia. Paraffinic crude oils are produced in some areas of North America and northern Asia. Mixed crude oils are produced in the Middle East.

The composition of mineral oils depends on that of the crude oils from which they are manufactured. There are two kinds of mineral oils: naphthenic and paraffinic.

Refining Process

Mineral oils are manufactured from distillate of heavy light oil and light lubricant oil by the process shown in Fig. 7. Where naphthenic oils are refined, acid treatment followed by clay filtration is also used. In the case of paraffinic oils dewaxing is part of the refining process. Examples of the composition of a naphthenic oil and a paraffinic oil are shown in Table 5. It is seen that in both paraffinic and naphthenic oils the amount of paraffinic compounds is greater than the amount of naphthenic compounds.

To obtain good dielectric characteristics, the amounts of nitrogen compounds and sulfur compounds should be as small as possible. However, excessive refining also decreases the amount of aromatic hydrocarbons. Decrease of the amount of aromatic hydrocarbons means a decrease in hydrogen absorption, and decrease of the amounts of both aromatic hydrocarbons and sulfur compounds means a decrease in oxidation stability. It is known that hydrogen adsorption relates to the partial discharge characteristics of oil (11,12) and that aromatic hydrocarbons have high hydrogen absorption. It is also known that coexistence of aromatic hydrocarbons and sulfur compounds is effective for oxidation stability. Therefore, refining must be performed so that the insulating oils maintain balanced characteristics. The optimum amount of aromatic hydrocarbons is 10 wt% to 20 wt%. In this case the amount
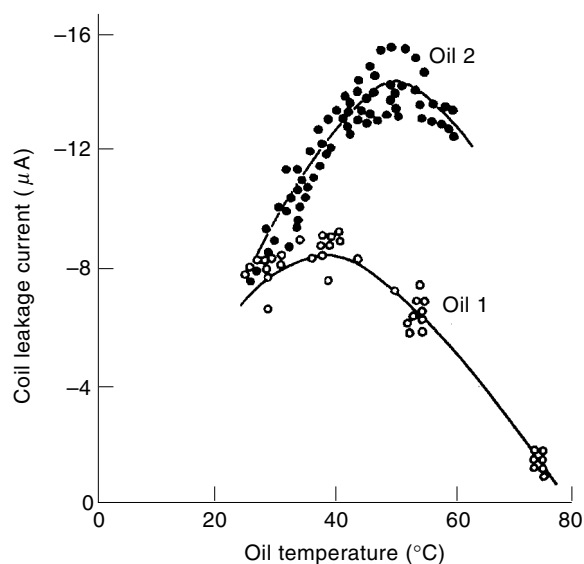

Figure 6. Oil temperature dependence of coil leakage current.

Naphthenic oil

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┌──────────────┐   ┌──────────────┐   ┌──────────────┐
│ Atmospheric  │───│ Vacuum       │───│ Solvent      │
│ distillation │   │ distillation │   │ refining     │
└──────────────┘   └──────────────┘   └──────────────┘

                   ┌──────────────┐   ┌──────────────┐
                   │ Hydrogenation│───│ Clay         │
                   │              │   │ filtration   │
                   └──────────────┘   └──────────────┘
```

Paraffinic oil

```
┌──────────────┐   ┌──────────────┐   ┌──────────────┐
│ Atmospheric  │───│ Vacuum       │───│ Solvent      │
│ distillation │   │ distillation │   │ refining     │
└──────────────┘   └──────────────┘   └──────────────┘

         ┌──────────────┐   ┌──────────┐   ┌──────────────┐
         │ Hydrogenation│───│ Dewaxing │───│ Clay         │
         │              │   │          │   │ filtration   │
         └──────────────┘   └──────────┘   └──────────────┘
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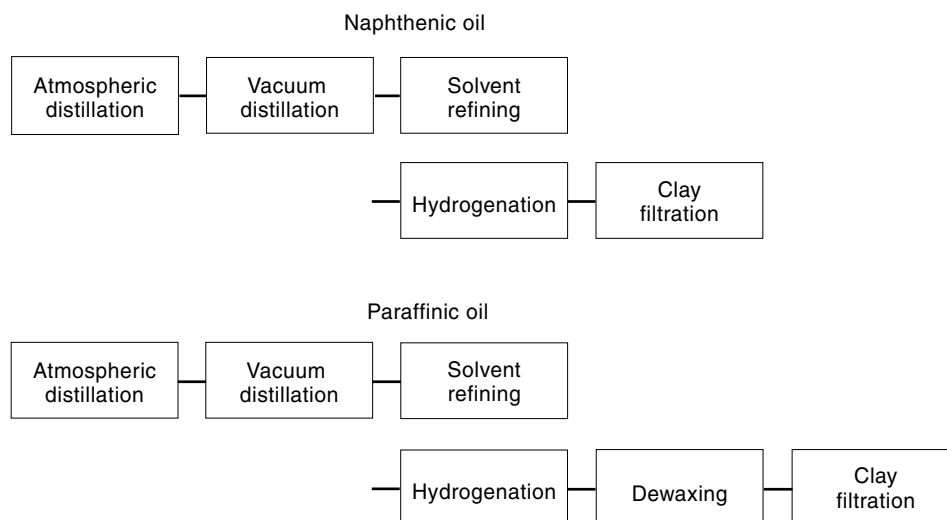
Figure 7. Refining of insulating oils.

of sulfur compounds is at least 0.5 wt%. Among them there are some corrosive sulfur compounds, but the amount of those is very small.

In some cases, oxidation stability can be corrected through the addition of oxidation inhibitors.

Characteristics of Mineral Oils

In Table 6 characteristics of some naphthenic and paraffinic transformer oils are shown. The higher pour point of the paraffinic oil is owing to the larger amount of paraffinic hydrocarbons in it. In the 1970s and 1980s the dielectric properties, compatibility with insulating materials, thermal stability, and other properties of paraffinic oils were investigated, and it was proved that various properties of paraffinic oils are by no means inferior to those of naphthenic oils, except for their higher pour points. To lower the pour points of paraffinic oils, pour point depressants are added. Mixing of alkylbenzenes with paraffinic oils is also effective for this purpose. An example of mixture of alkylbenzene and paraffinic oil is shown in Table 6. In this mixture a pour point depressant has also been added. The lowering of the pour point is seen.

Applications of Mineral Oils

Mineral oils are used for transformers, oil-filled (OF) cables, pipe-type oil-filled (POF) cables, capacitors, and circuit breakers. The greatest use is in transformers. Specifications for mineral oils are given in IEC 60296, 60465 and ASTM D3487, D2297, D1818.

Table 5. Examples of Composition of Insulating Oils

Type of Oil	Sample No.	Proportion of C (%)		
		Paraffinic	Naphthenic	Aromatic
Paraffinic	1	60.1	29.7	10.2
	2	59.9	27.5	12.6
	3	61.8	29.7	8.3
Naphthenic	1	45.1	36.3	18.6
	2	49.0	39.0	12.0
	3	50.7	40.8	8.5

SYNTHETIC OILS

PCBs were among the best and most widely used synthetic insulating liquids for electrical machines, such as power capacitors and transformers, due to their superb electrical characteristics and nonflammability, until a total ban on their use and production was imposed, first in Japan in 1972, then in the USA in 1976, and then in Europe in 1985.

In the 1960s alkylbenzenes were initially developed for high-voltage cables in view of their superior gassing properties under high voltage stress, and especially for use with synthetic paper.

At the time PCBs were banned, other kinds of synthetic aromatic hydrocarbons such as alkylnaphthalenes and alkyldiphenylethanes had been developed as candidates for improvements on mineral oils, but because of their higher cost, they had not been put into practical use. PCBs were then replaced mainly by these new aromatic hydrocarbons.

Aromatic Hydrocarbons

Alkylbenzenes consist of a benzene ring and an alkyl group of the straight-chain or branched-chain type. Alkylbenzenes are

Table 6. Characteristics of Mineral Transformer Oils

Property[a]	Paraffinic Oil 1	Paraffinic Oil 2[b]	Naphthenic Oil
Flash point (°C)	144	148	140
Kinematic viscosity (m²/s)			
40°C	7.8×10^{-6}	9.6×10^{-6}	7.9×10^{-6}
100°C	2.2×10^{-6}	2.5×10^{-6}	2.1×10^{-6}
Pour point (°C)	-25	-45	<-45
Permittivity			
80°C	2.1	2.13	2.16
tan δ (%)			
80°C	<0.01	<0.01	<0.01
ρ ($\Omega \cdot$ m)			
80°C	$>10^{13}$	$>10^{13}$	$>10^{13}$

[a] tan δ = dissipation factor; ρ = volume resistivity.
[b] Containing azkylbenzene and pour-point depressant.

mainly used for high-voltage cables, including cables with synthetic paper, as they have excellent compatibility with plastics. They can be blended with mineral oil to improve its gassing properties and thermal stability.

In IEC 60867, alkylbenzenes are divided into three classes according to their viscosity and flash point.

Alkyldiphenylethane (phenylxylylethane), alkylnaphthalene (diisopropylnaphthalene), and methylpolyarylmethanes (blends of benzyl- and dibenzyltoluene and blends of benzyltoluene and diphenylethane) are mainly used for high-voltage power capacitors and also used for instrument transformers. Because all of these liquids consist of two benzene rings with much shorter-chain alkyl groups than in alkylbenzene, their aromatic contents are higher than those of alkylbenzene, and their resistance to partial discharge is very high. They have excellent dielectric properties and also good compatibility with plastic film, especially with the polypropylene film currently used for capacitors; but all of them have lower permittivity (2.2 to 2.5) and flash point (130°C to 150°C) than PCBs. In some cases, they are stabilized by epoxiside or antioxidant. Their properties are also specified in IEC 60867.

Silicone Liquids

The silicone liquids currently used for electrical machines are polydimethylsiloxanes and have a variety of viscosities and flash points. Properties of a silicone liquid with a kinematic viscosity of 40 mm^2/s at 40°C are specified in IEC 60836. They are used mainly for special transformers, due to their good thermal stability at higher temperature and better flow at lower temperature than mineral oil and because they are not very flammable. They are also sometimes used for capacitors and cables.

Organic Esters

Dioctylphthalate (DOP) and diisononylphthalate (DINP) have been used as substitutes for PCBs, especially for capacitors, because they have higher permittivity (4.5 to 5.5) and flash point (200°C to 240°C) than aromatic hydrocarbons. Di-2-ethylhexyl orthophthalate (DOP) is specified in IEC 61099 as a capacitor ester (type C1). As not easily flammable liquids, phosphoric acid esters such as tricresyl phosphate (TCP) and trixylenyl phosphate (TXP) are used as blends with aromatic hydrocarbons. Generally speaking, these esters have high permittivity and high inherent resistance to electrical stress, but as manufactured they contain much water and impurities and their dielectric dissipation factor is very high, so they must be carefully dehydrated and purified before impregnation and often need an antioxidant or scavenger.

Recently, organic tetraester liquids have been introduced in transformers because they are less flammable. Their fire point is higher than 300°C, but their viscosity is low compared with that of currently used mineral oils. The same precautions should be followed as mentioned above, and additives are effective as in the case of other organic esters.

Tetrahydric alcohol and a mixture of monocarboxylic acid with suitable stabilizing additives are also specified in IEC 61099 (type T1).

Polybutenes

Polybutenes can have a large range of viscosity (1 mm^2/s to 10^5 mm^2/s at 40°C), depending on polymerization. These liquids are now used mainly in hollow cables (pipe-type cables) and to some extent in low-voltage capacitors. Polybutenes are specified in IEC 963 and classified into three classes, mainly depending on their viscosity. They are selected according to the specific application.

VEGETABLE OILS

Vegetable oils (castor oil, rapeseed oil, etc.) are basically triglyceryl esters of fatty acids, and the fatty acids can be saturated or unsaturated. They were once used for cables and capacitors, and are now mostly used for the impregnation of dc capacitors and especially energy storage capacitors, as they have high permittivity. They have not been used for ac power capacitors, as they have poor dielectric dissipation factors. Recently, however, they have been tried for use with metallized polypropylene films, with which they have good compatibility, and their dissipation factor and gas-absorbing ability have been improved by blending them with aromatic hydrocarbon liquids.

LIQUIDS FOR POWER TRANSFORMERS

Transformers were developed and began to be manufactured in the mid 1880s in Hungary, the USA, the United Kingdom, and France. In the years 1886 to 1891, manufacturers began to use oils for insulation transformers. Such oils (transformer oils) are specified in IEC 60296 and 60836 and in ASTM D3487 and D4652.

Transformer oils must have the following properties:

1. High dielectric strength and low dielectric losses
2. Good cooling power (mainly dependent on viscosity)
3. High chemical stability and high resistance to oxidation
4. Good compatibility with insulating materials
5. Low corrosive sulfur content
6. Low viscosity and good fluidity over a wide temperature range (low pour point)
7. Sufficient source of supply
8. High flash point
9. Nontoxicity

Of these, properties 1 and 2 are most important from the viewpoint of transformer performances.

Mineral Transformer Oils

Mineral oils have been used as transformer oils since the beginning of their manufacture. When properly refined, mineral oils have various excellent properties mentioned above. At present, mineral oils are used over wide range of transformer capacity, from distribution transformers to ultrahigh-voltage transformers.

Mineral oils are manufactured by refining crude oils. Depending on the composition of the crude oils, there are two kinds of mineral oils: naphthenic and paraffinic. The pour points of paraffinic oils are generally higher than those of naphthenic oils.

Sometimes mineral oils are mixed with each other or with other oils. The mixtures may be between oils of the same type,

between naphthenic and paraffinic oils, or with nonmineral oils. Some specifications can be found in IEC 60296. In some countries, mixtures of mineral oils and alkylbenzenes are used as transformer oils. Such oils have high resistance to oxidation, low corrosion, and low pour point. In the case of paraffinic oils, because of their relatively high pour points, pour-point depressants are added.

Because oils are oxidized under air, small amounts of antioxidants are added to some mineral oils, especially in Europe and North America. Such mineral oils are classified in IEC 60296 and ASTM D3487. However, in some countries mineral oils with antioxidants are not used.

In 1970s some flashover faults were found in ultrahigh-voltage transformers due to flow-induced electrification (streaming electrification). Factors that affect this phenomenon are transformer design (especially the flow rate of the oil), oil temperature, and properties of the insulating oils such as the volume resistivity and electrostatic charging tendency. Flow rates of oil have been controlled in some transformers to suppress this phenomenon. It is said that 1,2,3-benzotriazol (BTA), which has been known as a deactivator agent for metals, suppresses this phenomenon. In some countries a small amount of BTA has been added to mineral oils for high-voltage and high-power transformers for that purpose.

Synthetic Transformer Oils

Ordinarily flash points of mineral transformer oils are around 150°C. Therefore, mineral oils are not so desirable for transformers in trains and indoor substations. For those uses it is desirable to use nonflammable or less-flammable transformer oils. PCBs are nonflammable and are the most desirable oils for such applications. However, PCBs are no longer environmentally acceptable. Since they were banned, no transformer oils have been found that have the desired nonflammability.

Silicone (polydimethylsiloxiane) liquids have been put into use. These liquids (described in IEC 60836) have high fire points and good oxidation resistance, and are classified as less-flammable liquids in the National Electrical Code in the USA. They are often used for transformers of trains, and in some countries they have been used for distribution transformers.

Some polyolester liquids (described in IEC 61099) are used for transformer oils on account of their good thermal stability and low hydrolysis in the presence of water. Midel 7131 (The Micanite and Insulators Co.) and Enviro Temp 100 (RTE Co.) are examples. Mixtures of flon 112 and tetrachloroethylene such as Formel.NF (ISC Chemicals Ltd.) have been developed for transformer use. This liquid has environmental problems because of the flon 112. However, tetrachloroethylene is non-flammable, and it and its mixtures with mineral oils have been classified as nonflammable by Factory Mutual.

As previously mentioned, high-molecular-weight hydrocarbons with fire point higher than 300°C are classified as less-flammable oils in the National Electrical Code and are used for transformer oils. In Table 7 properties of some transformer oils are shown.

LIQUIDS FOR POWER CABLES

Oil-immersed power cables were developed and put into use in the 1880s, and a historic milestone in recent engineering and industrial progress was established by the invention and development of the oil-impregnated or oil-filled (OF) power cable by Emanuelli in 1923. OF cables are impregnated with oils without voids or moisture and then hermetically sealed to avoid damage and harmful effects from the surroundings.

From the early stage of OF cables, naphthenic oils have been mainly used because of their low pour point and high

Table 7. Properties of Some Insulating Oils

Property[a]	Mineral Oil	Silicone Liquid	Ester Oil	Mixture[b]	Tetrachloroethylene
Flash point (°C)	150	314	242	Non[c]	Non
Fire point (°C)	160	360	304	Non	Non
Ignition point (°C)	332	—	415	Non	Non
Specific heat (J/kg · K)	209×10^3	1.42×10^3	1.76×10^3	—	—
Specific gravity:					
25°C	0.89	0.96	0.98	1.62	1.62
Kinematic viscosity (m²/s):					
25°C	11×10^{-6}	50×10^{-6}	76×10^{-6}	0.88×10^{-6}	0.8×10^{-6}
100°C	2.5×10^{-6}	16×10^{-6}	31×10^{-6}	—	—
Pour point (°C)	−50	−55	<−45	−33	−22
Permittivity:					
25°C	2.2	2.7	3.2	2.36	2.37
tan δ (%):					
25°C	0.01	0.01	0.24	0.1	0.5
100°C	0.09	0.009	(80°C)	(23°C)	(50°C)
BDV (kV/2.5 mm):					
25°C	55	60	64	70	43
ρ (Ω · m):					
23°C	—	—	—	1×10^{13}	—
25°C	—	—	—	—	1.8×10^{11}
80°C	8×10^{12}	6×10^{13}	7.6×10^{12}	—	—

[a] tan δ = dissipation factor; BDV = breakdown voltage; ρ = volume resistivity.
[b] Flon 112+ tetrachloroethylene.
[c] Nonflammable.

stability under high stress, but with the progressive improvement of process technology for refining crude oil, paraffinic crude oils and mixtures of naphthenic and paraffinic oils have also been used because of their wider availability.

Aromatic content in mineral oil is also important, and in some cases synthetic aromatic hydrocarbons are added. Pure synthetic aromatic hydrocarbons, mainly alkylbenzenes, are also used, especially for ultrahigh-voltage power cables, because of their compatibility with synthetic papers, excellent stability under high stress, and sufficient source of supply.

Polybutenes are used for hollow power cables because of their wide range of viscosity.

Liquids for cables are specified in IEC 60465 (mineral oils), 60836 (silicone liquids), 60867 (aromatic hydrocarbons), and 60963 (polybutenes).

Cable oils must have the following properties.

1. High dielectric strength and high volume resistivity
2. Low dielectric losses and low dielectric constant
3. Low viscosity and good fluidity over a wide temperature range (low pour point)
4. High chemical stability and high resistance to oxidation
5. Low temperature coefficient of expansion
6. Sufficient source of supply
7. Nontoxicity and environmental safety

Of these, properties 1, 2, and 3 are most important from the viewpoint of power cable performance.

LIQUIDS FOR SWITCHGEARS

Liquids for switchgear (switchgear oils) must have arc suppression properties and high dielectric strength. Arc suppression properties are basically due to the high thermal conductivity of hydrogen gas produced by the decomposition of switchgear oils. Thus it is desirable that liquids easily produce hydrogen gas and that the amount of free carbon produced by their decomposition be small. Good insulation, requires not only high dielectric strength, but also rapid insulation recovery after interruption of electric arcs.

Besides these properties, it is desirable that switchgear oils have chemical stability to maintain good dielectric properties, and that they be compatible with the solids used. Insulating oils that have the above-mentioned properties are mineral oils. Switchgear oils are specified in IEC 60296 and ASTM D387. They are classified in the same classes as transformer oils.

The kinematic viscosities of insulating oils in these classes are relatively low: for insulating oils at 40°C classified in IEC 60296 as Class I and Class IA, Class II and Class IIA, and Class III and Class IIIA they are $\leq 16.5 \times 10^{-6}$ m²/s, $\leq 11.0 \times 10^{-6}$ m²/s, and $\leq 3.5 \times 10^{-6}$ m²/s, respectively. The kinematic viscosities of insulating oils at 40°C classified in ASTM D3487sa Type I and Type II are $\leq 12.0 \times 10^{-6}$ m²/s. Low kinetic viscosity allows mechanical parts of switchgears to perform freely, and oil flows owing to hydrogen gas evolved by decomposition of switchgear oils to be easily produced and facilitate arc suppression.

LIQUIDS FOR HIGH-VOLTAGE CAPACITORS

The capacitor is one of the oldest electrical components. An oil-immersed capacitor was developed in the 1850s, but the fundamental technologies of modern oil-impregnated and oil-filled high-voltage power capacitors originated with those of high-voltage power cables.

After PCBs were developed around 1930, PCBs (mainly trichlorobiphenyl for high-voltage power capacitors) were used for can-type capacitors and mineral oils were used for large tank-type capacitors, until PCBs were recognized as environmentally hazardous. PCBs were also used for a short period as the impregnant for plastic film (polypropylene) dielectrics of both paper–film and all-film types. Just after the ban on PCBs, those impregnants were replaced by aromatic hydrocarbons. As the aromatic contents of these hydrocarbons are very high, they are very suitable for the impregnation of high-voltage capacitors with sharp-edged foil electrodes.

Because aromatic hydrocarbons are more flammable than PCBs, silicone or blended oils of aromatic hydrocarbons and phosphoric acid esters have been used for high-voltage capacitors as less-flammable liquids for limited use; but recently dry capacitors have been developed for use where fire-resistant materials are strictly required.

To minimize the dielectric thickness, self-healing technology originally developed for low-voltage capacitors has recently been applied also for high-voltage capacitors. In this case, as metallized paper or film is used, and therefore compatibility between the impregnant and the solid material is very important, impregnants such as organic esters are used.

Liquids for high-voltage power capacitors are specified in IEC 60836 (silicone liquids), 60867 (aromatic hydrocarbons), and 61099 (organic esters).

Liquids for high-voltage capacitors must have the following properties:

1. High dielectric strength and high volume resistivity
2. Low dielectric losses and high dielectric constant
3. High stability under high voltage stresses and high partial discharge resistance
4. Good compatibility with film materials
5. High chemical stability and high resistance to oxidation
6. Low temperature coefficient of expansion
7. Nontoxicity and environmental safety
8. Sufficient source of supply

Of these, properties 1, 2, and 3 are most important from the viewpoint of high-voltage capacitor performance.

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