

Life Cycle of Mineral Based Insulating Oil – A Review

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ABSTRACT: Mineral based insulating oil is obtained from distillation of crude oil. Its few intrinsic properties such as high breakdown voltage, sufficiently low viscosity, high interfacial tension, strengthens its candidature as an insulating oil which could be used in transformers and other switchgears. Insulating oil in a transformer performs various tasks ranging from acting as an insulator between the active components to dissipating heat generated due to operational loads, it also quenches arc generated due to any malfunction inside the transformer tank, the transformer oil, through its testing also helps us assess the condition of the transformer. While performing the tasks at bay the oil performance deteriorates with time, this fall in properties of oil is majorly due to the electrical and thermal stresses that it undergoes during its operational life time. This paper reviews the life cycle of a mineral based transformer oil, the roles it plays during its service life and the problem that modern world faces with its disposal.

Earlier review studies have primarily adopted a unidirectional approach, with discussions limited to specific stages such as oil production, application, or maintenance. In contrast, a comprehensive framework is provided in the present review, covering the complete lifecycle of mineral-based insulating oil.

A holistic overview is presented, including crude oil sourcing, compositional variations based on geographical origin, refining processes, insulation applications, degradation mechanisms, reclamation processes, and end-of-life disposal. Regulatory requirements governing disposal and environmental protection are also discussed in detail, particularly in view of the non-biodegradable nature of mineral insulating oil.

KEYWORDS: Mineral Oil, Heat dissipation, oil testing, solvent extraction, reclamation.

I. INTRODUCTION

Transformers are considered critical assets in industrial power systems. The ageing of transformers is directly influenced by the condition of the insulation systems present within them. The condition of both oil and paper insulation has been closely linked to the lifetime assessment of transformers. Ageing assessment is considered essential for minimizing failure risks, as aged transformers are more susceptible to breakdowns and operational failures. Several challenges are associated with insulation ageing, including safety hazards such as fire and explosion risks, efficiency losses, and significant capital expenditure associated with corrective maintenance following equipment failure. Such risks can be minimized through regular monitoring of oil and solid insulation condition.

During continuous operation, deterioration of insulating properties occurs due to electrical and thermal stresses imposed by operational loading conditions. Accelerated ageing is induced as a result of these stresses. In addition to operational stresses, exposure to adverse environmental conditions at the installation site also contributes significantly to insulation degradation.

In regions characterized by high humidity, increased ingress of moisture into transformers is facilitated, resulting in deterioration of oil and insulation performance. In coastal environments, salt-laden moisture not only increases moisture content in the oil but also accelerates corrosion of transformer components, thereby compromising mechanical strength. Similarly, transformers installed in industrial environments are continuously exposed to atmospheric pollutants.

Oil contamination, corrosive sulfur reactions, and copper sulfide deposition on windings are induced by the presence of particulate matter, sulfur compounds, and chemical pollutants. These processes result in increased conductivity within

paper insulation and adversely affect its dielectric performance [1]. The presence of hydrogen sulfide, another corrosive sulfur species, has been shown to reduce the mechanical strength of cellulosic insulation paper. Mechanical properties such as modulus of elasticity, shear strength, and bulk volume have been reported to decrease due to hydrogen sulfide exposure. Additionally, a reduction in glass transition temperature has been observed, resulting in increased material softness and enhanced susceptibility to moisture and corrosive species migration [2].

The formation and deposition of copper sulfide on copper windings and adjacent paper insulation have been attributed to sulfur attack on metallic conductors. Electrical conductance losses and distortion in electric field distribution have been observed in regions where copper sulfide deposition occurs. The penetration of copper sulfide into insulation layers occurs gradually and contributes to long-term degradation and reduction in transformer lifespan [3].

Transformers operating at higher altitudes, such as in Himalayan regions, are subjected to higher operating temperatures for equivalent loading conditions due to reduced cooling efficiency resulting from lower air density. To address this issue, derating requirements for transformers operating above specified elevations have been established in IEC 60076 standards. Moisture and oxygen ingress into transformer oil occurs through defective gaskets, ineffective breathers, and air present in the headspace of the transformer. This ingress results in deterioration of insulating performance, and the rate of degradation increases with increasing operating temperature. The presence of water in oil has been shown to reduce dielectric strength and electrical resistivity, thereby adversely affecting electrical performance parameters such as partial discharge inception voltage.

Maintenance and reclamation of mineral insulating oil are considered essential for two primary reasons. First, the operational life and performance of transformers can be extended through proper oil maintenance. Second, due to its non-biodegradable nature, mineral oil poses significant environmental risks. Environmental contamination may occur due to the presence of hazardous compounds such as polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and heavy metals. These contaminants may degrade soil quality, reduce soil fertility, alter microbial activity, and enter the food chain through plant uptake. To mitigate such risks, strict regulatory frameworks have been established for oil disposal and remediation of contaminated soil.

With its introduction in late 19th century mineral oil has been a part of various studies and research. It was a resource which was available in a huge amount due to burgeoning oil industry. Its low cost, easy availability and low thermal conductivity pushed it even further to a stage where it became a global phenomenon to use mineral oil as an insulator inside the switchgears and mostly transformers. Increasing developments in the power industry, ranging from electricity generation to transmission, saw a great increase in the usage of mineral oil. By the early 20th century the industries began to understand the importance of the enhanced properties of these oils and thus came the advancements in the production and refining techniques. Alongside, the organizations like ASTM (American Society for Testing and Materials) and IEC (International Electrotechnical Commission) began setting up the standards which further brought a great deal of refinement in the properties of the oil and better safety measures during operations.

In the mid-20th century the industries started to acknowledge the problems pertaining to the mineral based transformer oil, its high flammability, its low stability against oxidation and the presence of PCBs, a synthetic organic chemicals with chlorine atoms attached to biphenyl molecules. PCBs were introduced to enhance the oxidation stability of oil, it improved oil's thermal stability and also added to its insulating properties. These PCBs were carcinogenic in nature (classified by EPA and WHO as human carcinogens), it affected neurological and reproductive systems. It degraded slowly and thus was considered an environmental contaminant. Later in the late 20th century various governmental agencies across USA and Europe, imposed ban on the production and usage of PCBs as an additive also there were steps taken to either replace the PCB inked oil in use or reduce its concentration using de-chlorination and adsorption using activated carbon.

Crude oil

Crude oil is available across the globe in abundance, but in discrete amounts. While some countries enjoy the luxury of controlling the barrel prices, there are some which largely depend on the oil being imported from outside borders. Crude oil has been source of more than ten valuable products and raw materials. It fulfils the need of fuel oils such as petroleum, diesel, LPG (liquefied petroleum gas), jet fuel oil, bunker oil, etc., we also get industrial raw material such as naphtha, bitumen (asphalt), petroleum coke and sulfur. Crude oil is also a source of some special oils like mineral

oil, white spirit and paraffin wax, beside this the crude also helps to produce hydrocarbons in such a boiling range where it can be further utilized in pharmaceutical industry.

Extraction of valuable products from crude oil requires complex processes involving physical and chemical treatments, the steps involve atmospheric distillation, vacuum distillation, cracking, reforming, hydrotreating, coking, polymerization, purification and many more depending on the application and product desired. This study will revolve around the landscape of production of mineral oil from crude and the latest advancements in the field based on requirements. The study will also include its usage as an insulating oil and stages and steps of disposal after the completion of its service life. The products obtained from the distillation of the crude differ in their properties depending upon the operational conditions, such as temperature and pressure at which it is produced and further the severity of refining processes. Mineral oil which is to be used in a transformer as an insulating oil needs to hold some task specific characteristics which are defined by the standards given by ASTM (D 3487), IEC (60296) and IEEE (guide C57.106).

Crude oil refining is a complex process involving chemical and physical processes to reach to a product which is valuable either due to its intermediate application in the industries or as a final good. The refining of crude is basically a later stage, reached when the distillation process is over. The operation starts with fractional distillation of crude oil where the constituent compounds separate from each other on the basis of different boiling ranges. The top section of the column which is at a lower temperature given the highest volatile compound whereas the bottom product from the column also known as residue, is the one which is least volatile in nature. The products obtained from top to bottom are refinery gases (liquefied petroleum gas), gasoline (petrol), naphtha (petrochemicals), jet fuel oil, kerosene oil, diesel, lubricating oil (mineral oil), fuel oil (ships, sub-marines), tar (road construction), wax, asphalt (road construction), residue. The resulting compounds are not pure and thus further refining is required. Properties of the final product sets the criteria for the refining operations and its severity, this can be understood using an example of petroleum. Petrol with higher octane number is enriched in branched hydrocarbons (iso-paraffin) and thus its processing requires reforming, alkylation and isomerization steps while the petrol with lower octane number requires minimal refining steps after distillation and purification

Mineral Oil

Mineral oil falls under the category of lubrication oil and it is obtained from the lower section of the atmospheric distillation column. Mineral oil obtained from distillation contains hydrocarbons with number of carbon atoms ranging from 8 to 60. The molecular weight of the constituent compounds ranges from 28.2 g/mol to 843.6 g/mol and the boiling point from 150 °C to 894 °C. From the above data it is quite clear that mineral oil is composed of a large number of hydrocarbons and that too of diverse nature. The primary categorization of compound is done on the basis of the structures. The first category is saturated paraffin (alkanes) which are straight chain and branched compounds with single bond connections throughout. The second category is saturated naphthenes which are similar to paraffins in a manner that it also contains single bond throughout, but naphthenes are ring compounds or alkyl groups attached to it. The third and the last category is that of aromatic compounds, containing double bonded ring compound either attached to another ring or an alkyl group. The concentration of these compound in an oil is a result of its origin and this is what governs the refining steps involved and its property as an insulating material. The table below shows the resulting oil concentration based of their origin.

Table 1: Composition of petroleum crude oil based on region (Source EFSA 2012)

Sourced from (Region)	Physical Appearance	Composition
North Sea	Transparent.	High paraffinic and naphthenic content.
East Asia (China, Indonesia)	Low transmissivity.	High paraffinic and naphthenic content.
Arabian	Brownish in appearance with high viscosity.	Intermediate concentration of paraffins and naphthenes.
Nigerian	Brownish in appearance with high viscosity.	High naphthenes and aromatics content.
South America	Black in appearance.	High naphthenes and aromatics content.

The properties of mineral insulating oil are determined by its chemical composition and constituent hydrocarbon structures. Variations in crude oil source location result in significant differences in chemical composition and insulation performance characteristics.

Oils sourced from the Middle East and East Asian regions (China, Indonesia and Malaysia) are characterized by higher paraffinic hydrocarbon content, whereas oils obtained from the North Sea exhibit mixed paraffinic and naphthenic composition. Oils sourced from Nigeria and South American countries (Venezuela, Brazil) are characterized by higher naphthenic and aromatic hydrocarbon content.

Oxidation stability has been shown to be strongly influenced by paraffinic content, with higher paraffinic concentration resulting in improved stability due to the presence of chemically stable carbon-carbon bonds. Oils rich in aromatic and naphthenic content have been reported to exhibit higher dielectric breakdown strength.

Aromatic hydrocarbons play a critical role in gas absorption and evolution behavior under electrical stress conditions. Oils with low aromatic content tend to exhibit positive gassing tendency (gas evolution), whereas oils with higher aromatic concentration exhibit gas absorption behavior (negative gassing tendency).

Naphthenic content has also been associated with improved low-temperature performance, reduced wax formation tendency, lower pour point, and improved cooling characteristics. Additionally, sludge formation tendency has been observed to decrease with increasing aromatic content.

Highest concentration of the constituent component helps characterize mineral oil as paraffinic, naphthenic or aromatic. Along with these oil contains other impurities which include olefins and alkenes, which under conducive environment form additional products. Nitrogen, oxygen and sulfur present in heterocyclic forms are responsible for poor oxidation stability of the oil. Sulfides, disulfides and mercaptans react with other metals. Other polar compounds such as ketones, aldehydes and alcohols convert to other unwanted acids. (Ref: Mineral insulating oil in transformers).

Atmospheric distillation is the first step where the crude oil separates into different components. The product obtained is impure and contains components of different boiling range. The second stage to distillation is the vacuum distillation. The operating pressure is less than the atmospheric so that the boiling point could be reached at a lower temperature thereby avoiding the decomposition of the compounds.

The table below contains the products obtained from distillation of crude oil.

Table 2: Fractions obtained from distillation of crude oil. (Ref: Nelson, W. L. (1958) – "Petroleum Refinery Engineering," McGraw-Hill)

Fractions obtained	Boiling Range (°C)	Usage
Gases (Methane, Butane)	< 40 °C	Major components in CNG and LPG.
Petroleum	80 °C -200 °C	Motor vehicles.
Kerosene	120 °C -250 °C	Jet fuel
Diesel	250 °C -350 °C	Heavy automotive
Lubricating Oil	350 °C -500 °C	Transformer oil, Engine oil for ships, submarines
Bitumen, Tar, Asphalt	>500 °C	Road construction

Mineral oil obtained from distillation and fractionation column still contains components in the boiling range of 350 °C to 500 °C. Mineral oil employed as an insulator in a transformer holds some specific properties necessary for such operations. For being able to perform as such, the mineral oil needs to be narrowed down in terms of constituent components. To provide better electrical and chemical properties the oil is further refined according to the requirements.

Refining of Mineral oil

Refining of mineral oil is done to remove the unwanted byproducts, polar compounds, aromatics and other impurities. Refining of oil improves its stability towards oxidation. It improves its other electrical and chemical properties to ensure its compliance as required by the standards, ASTM D3487, IEC 60296, etc. Refining includes solvent dewaxing, solvent extraction, hydrogen based refining steps (Hydro-processing and hydro-treatment) and clay treatment or adsorption refining (used as secondary refining step or as a regeneration step).

II. SOLVENT EXTRACTION

It is the first stage of treatment carried out majorly to remove the aromatic and sulfuric compounds (aromatics not discussed in this paper). Mineral oil contains various types of sulfuric contents which includes mercaptanes, disulfides, organic sulfides, it also contains sulfuric compounds which act as natural antioxidants [4].

Sulfur present in mineral oil can be categorized as reactive and passive. Elemental sulfur and mercaptans are highly reactive and cause metal corrosions. The stable or passive sulfur (thiophenes) do not stay as such for long and due to various electrical and thermal stresses it breaks into a corroding compounds [5].

Due to superior physicochemical and electrical properties of copper, it is employed to make windings in transformers. The kraft papers which wraps the winding and the mineral oil in which this whole assembly is dipped provide an insulation between the active parts. When the reactive sulfur comes in contact with copper, it forms copper sulfide (Cu₂S). This copper sulfide mixes in oil, adheres on the surface of the paper insulation and even on the exposed metal winding surface. This adherence causes a drop in electric strength of the insulations which eventually leads to breakdown of the instrument. IEC 62535/IS 16310 is the test method used for the “detection of potentially corrosive sulfur in used and unused insulating oil”. As per the procedure defined in the standard, if the amount detected on the copper strip and the insulating paper used in the experiment is less than 5 mg/kg, then the oil is considered as non-corrosive [6].

DBDS (dibenzyl disulfide) an aromatic organosulfur compound is used to provide oxidation stability to the oil, it even reacts with copper and other metals present in a transformer, reactor or other such devices to form metal sulfides, thus DBDS is also classified as potential corrosive sulfur [7].

Addition of metal passivators (like Toluitrazole-dialkyl-amine) act as a shield to metallic corrosion. These passivators adhere on the metal surfaces and act as protective layer. However, overloaded power transformers finds a depletion in concentration of these passivators which eventually puts metallic components, at the risk of corrosion. The minimum concentration of passivators required to put a halt to this sulfuric corrosion ranges between 25 mg/kg to 30 mg/kg [8]. Use of passivators also leads to a problem known as “passivation induced stray gassing”, in this the passivators under severe operational stresses release hydrogen and carbon oxides gases [9], which certainly defies the role of DGA as a fault diagnostic analysis.

Stray gassing is defined as the generation of gases at relatively low temperatures (100–200 °C) in transformer oil without the presence of electrical faults such as overheating or partial discharge. This phenomenon has been attributed to oil instability and the presence of metal deactivators, commonly referred to as passivators.

Passivators are used to protect copper conductors from sulfur-induced corrosion. Copper sulfide formation on winding surfaces and adjacent paper insulation has been shown to occur in the absence of passivation protection.

Stray gas formation, primarily involving hydrogen (H₂), carbon monoxide (CO), and carbon dioxide (CO₂), has been attributed to passivator decomposition under electrical and thermal stress conditions. Passivators, which are nitrogen-containing compounds, undergo decomposition and oxidation reactions, resulting in the formation of gases and chemically stable byproducts.

Oxidation reactions involving oxygen and insulating oil result in the formation of peroxides, organic acids, and free radicals, which subsequently react with passivators and contribute to stray gas formation.

The presence of stray gases complicates dissolved gas analysis (DGA) interpretation and may lead to inaccurate fault diagnosis. Therefore, comprehensive gas analysis, including evaluation of gas ratios, concentration trends, and correlation with passivator concentration, is considered essential [10].

Preventive measures include the use of high-quality inhibited oils compliant with IEC 60296 and IS 335 standards, reduction of oxygen ingress through conservator sealing methods such as rubber bladder systems, and optimization of transformer operating temperature.

Last two decades saw a sudden increase in the number of cases where failures in the transformer and reactors were narrowed down to presence of disulfide and other sulfur compounds, which caused insulation failure and thus the sweetening of transformer oil became important.

In one of the study three samples, unused mineral oil, used mineral and used mineral oil with inhibitor content were put to experiment, extraction method was used with “N-methyl-2-pyrrolidone (NMP)” as a liquid extractant. NMP was used due to its high selectivity, ease of experimentation and handling. 01% of water in NMP further improved the selectivity of the solvent. The oil samples were subjected to corrosive sulfur test as per IEC 62535, oxidation stability test as per IEC 61125 (test B & C) and other tests like SEM/EDX (on paper insulation from corrosive sulfur test), FT-IR and GC-MS were conducted. The final result suggested that for all three samples, NMP was efficient in removing the DBDS and other aromatic compounds that were initially present [11].

Another study using fuller’s earth and a simply modified catalyst (treated and activated fuller’s earth) was conducted. During modification of the clay, it was washed with methanol and dried, then it was placed in KOH solution and Dopamine aqua solution. Manganese oxide was added to the solution post which it was kept in the furnace for activation. The cycles of treatments required to reduce the sulfur content (DBDS) and turn it to non-corrosive, was nearly half for the modified catalyst in comparison to the fuller’s earth. Manganese has an affinity for sulfur and thus the cycle reduced for modified catalyst [12].

Nine different ionic liquids based on Imidazolium were studied. 1-butyl-3-methylimidazolium[FeCl₄] and 1-butyl-3-methylimidazolium[BF₄] were found to be most and least efficient respectively, in extracting DBDS present in the oil. High polarity, low viscosity and higher mass ratio (ionic liquid/oil) were the most suited criteria of the extractant as per the study [13].

Desulfurization of oil using adsorbents and liquid-liquid extraction was carried out. The properties of the two naturally available bentonite based adsorbents and a commercial sorbent were studied using nitrogen physical adsorption, mercury porosimetry and helium pycnometry. The result obtained reflected that despite the similar structure and nearly the same porous volumes of the naturally available sorbents, the one with lower amount of quartz and higher amount of smectite showed much better performance. Thus the potential or affinity of the individual mineral present in the sorbents also plays a key role in its performance. The study also concluded that the naturally available bentonite can not only be used to in desulfurization but, it can also be utilized in regeneration of the transformer oil. The extraction method employed two steps. First step was the extraction of DBDS using 1-methyl-2-pyrrolidone and the second step was the removal of extractant left in the oil using any of the sorbent used in the study [14].

In one of the experiment CeY, CuY, AgY adsorbents were prepared using liquid phase ion exchange method. NaY zeolite was placed in contact with Ce(NO₃)₃, CuNO₃, AgNO₃ solutions at certain experimental conditions. The obtained solution was filtered, washed and dried to obtain the above stated adsorbents. The study involved two kinds of oils, mineral oil and the silicon oil, both the oils showed difference in effectiveness with which the sulfur was removed, which suggested that due to change in the surrounding environment the interaction between the adsorbent and the adsorbate changes. All the three adsorbents performed well against the removal of DBDS and a few other sulfuric compounds [15].

Besides acting as a stabilizing agent against oxidation, the presence of sulfur in any form whether highly reactive or un-reactive, leads to corrosion of copper, silver or any other metal present in the transformer/reactor. The long duration of operations and the overloaded operational conditions further catalyzes this corrosion process. The problem can be tackled with the use of passivators, changing the oil with a new one or removal of sulfur using adsorbents, ionic liquids or liquid-liquid extractions process.

Hydro-processing, Hydro-treatment and Hydro-finishing

These procedures are related to refining of transformer oil with the help of various operations involving hydrogen. The treatment converts aromatic/un-saturated hydrocarbons present in the distilled oil to saturated hydrocarbons. Rather severe treatment (at higher temperature and pressure) could even lead to conversion of high boiling fractions to low boiling small chain petroleum fractions i.e. breaking of long chain hydrocarbons to smaller chained hydrocarbons, the process is termed as hydrocracking.

Pt, Pd and Ni catalyst supported over alumina and silica-alumina base were compared for hydrodechlorination of the transformer oil. Supercritical fluids acted as reaction media. The degree of dechlorination was highest in case of Ni, intermediate for Pd and lowest for Pt, the larger size of Ni metal and high metallic loading were the weighing factors. The change in reaction media also altered the dechlorination process. Dilution level of the supercritical fluid was amongst the influencing factor [16].

Another study comparing four insulating oils, of which one was hydrogenated, one was locally produced while the other two were imported i.e. different source of origin and method of production. On comparison the hydrogenated oil showed best electrical properties, lowest dissipation factor and highest dielectric strength along with highest volumetric resistivity. The study suggested the lowest electrostatic charging tendency of the hydrogenated oil, which makes it the safest of all the four types put under investigation [17].

Hydrogenated transformer oil was tested for various parameters, of which oxidation stability was one. Formation of various products such as acids, ketones and esters due to oxidation were studied using IR. All the observed curves on FTIR were overlapping each other, i.e. no additional group formed due to ageing. All differently aged oils were nearly similar in appearance. There were variations observed in the tan delta and resistance properties of the dielectric oil, the aged oil showed sudden increase in tan delta values after showing small deviations during the initial ageing runs. The resistivity values showed similar variations as that of dissipation factor. Other properties like permittivity, Interfacial tension and the viscosity remained constant throughout the ageing process [18].

Alkanes of the oil underwent beta-bond breakage and unwanted components like, sulfur, nitrogen, oxygen were effectively reduced through hydrocracking. This process improved the low temperature properties of the oil such as pour point and viscosity. Hydrorefining further reduced the concentration of the unwanted materials and gave a push to the properties of the oil at low temperature, it even improved its withstanding limit against oxidation stability test and other metal passivators [19].

This study utilized the accelerated ageing strategy to study the effect of insulating oil on different material of construction, i.e. rubber, paper insulation and the inner coating of the transformer. The components were aged in hydrogenated oil and a naphthenic based oil separately. The obtained result for interfacial tension, breakdown voltage, acidity and even tan delta showed superior performance of the hydrogenated oil over the other one considered in this investigation [20].

The role of transformer oil in a highly rated electrical equipment, not only as an insulating agent, arc quencher but also as a message carrier is highly influenced by its antioxidant and anti-ageing properties. This study considered a hydrogenated transformer oil aged under accelerated conditions and analyzed for paraffinic, naphthenic and aromatic content. FT-IR was used as tool to identify and even quantify the hydrocarbon in the categories stated above. The result reflected the increase in paraffinic hydrocarbon concentration and fall in naphthenic content, while the aromatic content remained the same. Theoretically, due to high activity of the aromatics there must be a change in its concentration but due to initial hydrogenation of the oil the concentration of the aromatics fall below the detection level of the FT-IR and thus its amount remains the same. The hydrogenated oil shows nearly no variation in color due to ageing, this may be asserted to its high refining during hydrogenation [21].

III. RECLAMATION AND DISPOSAL OF USED MINERAL OIL:

The recycling of the hazardous waste (here mineral oil) becomes important as it reduces the load over the landfill and the dumping yards, it is also important for conservation of resources. Being non-biodegradable and toxic in nature the recycling becomes even more important, as and when disposed it would degrade the soil and water quality which will certainly affect the nearby habitat.

The process adopted to recycle the waste material needs to use ESTs (Environmentally Sound Technologies). The use of such technologies is not only important to reduce emissions and discharges but also to make sure that the recovered item meets the quality standard as per the requirements.

The Ministry of Environment and Forests (MoEF) published “Guidelines for Environmentally Sound Recycling of Hazardous Wastes, 2008”. There were provisions made in Hazardous waste (Management Handling and Trans-boundary Movement) Rules 2008, to allow the regeneration and re-processing of the selected group of wastes. Later on the Central Government amended it and presently its nomenclature stands as “Hazardous and Other Wastes (Management and Trans-boundary Movement) Second Amendment Rules, 2023”.

The HW rules 2008 suggest four ESTs:

- 1) Vacuum distillation with clay treatment
- 2) Vacuum distillation with hydrotreating
- 3) Thin film distillation
- 4) Any other technology approved by MoEF

Other than these the ESTs approved by the CPCB (Central pollution control board) could also be used. The vacuum distillation with clay treatment is the most used reclamation technique in our country. Based on the condition of the transformer oil (to be re-refined), the distillation step could be included, whereas the other steps are, the neutralization step using alkali solution, the dehydration step and the filtration step (directly or with the help of clay).

The mineral oil or any kind of oil which is being utilized as an insulating oil inside an electrical equipment suffer property loss with time. This fall in intrinsic behavior of the oil is due to factors which include, operational conditions (load and duration of operation) which imposes thermal and electrical stress over the oil, atmospheric conditions (humidity, rain fall, wind, etc.) causes slow heat dissipation rate, ingress of moisture and other chemical stresses due to exchange of atmospheric gases (oxygen, carbon dioxide, hydrogen, etc.). Reclamation process helps to improve the behavior of the oil by removing sludge, reducing the acidity and other impurities using various tools. The non-biodegradable and carcinogenic nature of the mineral oil makes it even more important to regenerate the oil instead of disposing it. At present there are two standards which present the guidelines towards reclamations, IEEE Std 637 – 2007 (IEEE guide for the reclamation of dielectric oil and criteria of its use). The other method being the BS EN 60422:2013.

Two methods for reclamation namely, reclamation by percolation which is a continuous operation involving filtration, adsorption using fuller’s earth and reconditioning to remove polar impurities and moisture respectively from the oil sample. Reclamation by contact is a batch operation as it involves suspension of fuller’s earth (adsorbent) in the oil tanker which needs to be reclaimed. This process is more often used at laboratory scale to study the effectiveness of the adsorbent. Neutralization value, interfacial tension, moisture content, turbidity, viscosity, flash point, tan delta were amongst the properties which showed great improvement after reclamation. As the number of re-circulations increased the properties inched towards that of a new oil [22].

A reclamation study using two types of adsorbents namely fuller’s earth and laboratory generated bentonite (Algerian adsorbent clay) was carried out. The service oil was firstly reclaimed using the two adsorbents separately and then were subjected to accelerated ageing to study the fall in properties due to ageing after being regenerated. The oil reclaimed using the laboratory prepared bentonite had superior properties (water content, resistivity, color index, acidity and dissipation factor). A post ageing analysis for the same parameters revealed drop in the dielectric properties, but this drop was again higher for the oil treated with fuller’s earth on comparison to that treated with bentonite [23].

Another study to reclaim the serviced transformer oil using the acid treated bentonite and anti-oxidants reflected the importance of development of new methodology in the field. Here different combination of primary anti-oxidants are mixed in the ratio of 1:1:1. The primary anti-oxidants used were Butylated hydroxy toluene, Butylated hydroxy anisole, Propyl gallate, Alpha tocopherol, Ascorbic acid and Citric acid. The study concluded that the properties (flash point, breakdown voltage, water content and fire point) of the oil under investigation improved on treatment with bentonite and the anti-oxidants. The percentage increase in these properties varied with the kind and amount of anti-oxidant used [24].

Kaolin another adsorbent with the properties similar to those of bentonite and bauxite was utilized to carry out a laboratory investigation. Firstly the behavioral study of kaolin was carried out using EDX-SEM (energy dispersive X-ray spectrometer with scanning electron microscopy) and TGA (thermogravimetric analysis). Further the experimental investigation to assess the use of kaolin as an adsorbent and other governing factors such as its amount to be used, number of stages and the temperature to be implemented for the operation were studied. The results for the oil parameters (breakdown voltage, water content, viscosity, dissolved gas analysis, colour and acid number) reflected an improvement with increasing operational temperature and steps/stages. The study concludes with the regeneration of the Kaolin adsorbent via ignition at 750 degree celsius [25].

Another study was carried out which used the combination of four different adsorbents namely, silica gel (SG), activated carbon (AC), magnesium oxide (MO) and activated bentonite (AB). The paper outlines different steps involved in reclamation and later moves on to adsorption as a final step. The adsorbents not only follow physisorption but due to its activation prior to use it even follows chemisorption. The parameters like dissipation factor, total acidity number decreased while the resistivity factor and the color index improved which certainly shows the improved properties of the transformer oil which in turn improves its performance as a dielectric liquid [26]. All the reclamation steps involve generation of disposable wastes. These wastes are used for co-processing in cement kilns, incineration at Treatment Storage and Disposal Facilities (TSDFs) or any other ways through which energy or resources could be recovered as approved by the CPCB or authorized by SPCBs/PCCs (State Pollution Control Boards and Pollution Control Committees). Even the spent clay could be used for co-processing in cement kilns and/or as fuel in brick kilns.

IV. CONCLUSION

The dielectric properties of the mineral oil played a major role behind its implementation as an insulating agent in the instruments with active inner core. It found its largest application in the transformers and the switchgears. Due to its ease of availability and low cost, its use as an insulator got globalized. This globalization was more or less affected by the industrial revolution, which brought about a sudden sense of use of machines and energy as a resource. With its use over time, came along the committees/institutions which imposed a bubble of its use by setting parametrical limits, which in turn brought about a great deal on refinement in the finally used mineral oil. The oil producers across the globe incubated these changes. All along the non-biodegradable nature of the oil was being acknowledged and addressed. In the present scenario, the reclamation of used oil to obtain a final product with similar properties of new oil is considered as a widely accepted approach. Limited presence of oil reservoirs and generation of toxic/carcinogenic waste (being used for co-processing, as a fuel/source of energy or disposed through incineration) pushed the researchers to explore for other alternates.

The lifecycle stages of mineral insulating oil have been comprehensively discussed in this review. Mineral oil has been widely used in transformers for more than one and a half centuries due to its favorable electrical properties, availability, and cost-effectiveness.

Although increasing research attention has been directed toward biodegradable ester-based insulating fluids, mineral oil continues to be widely used due to its balanced performance and economic advantages. Recent research efforts have also focused on enhancing mineral oil performance through the incorporation of nanoparticles. However, challenges associated with thermal stability, electrical degradation, and environmental non-biodegradability remain significant. Increasing quantities of aged oil that cannot be regenerated are expected in the future. Therefore, improvements in refining processes, oil formulation, and end-of-life management strategies are considered essential for ensuring long-term sustainability.

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