ABSTRACT

The life of a transformer is linked to the fundamental role of insulating liquids to dissipate heat and protect the transformer's solid insulation. Historical developments affecting crude oil source and advances in refining technology mean that not all mineral insulating oils are made equal. Isoparaffinic oils in particular can offer enhanced oxidative stability, lower viscosity in colder temperatures, and superior heat transfer, resulting in improved reliability and utility for transformer operators

KEYWORDS

isoparaffinic, naphthenic, transformer oil, mineral insulating oil, liquid insulation

Not all mineral oils are equal

Exploring the history and technology behind mineral insulating oils

1. Introduction

Before Elihu Thomson, an electrical engineer working for Westinghouse in the US, patented the use of mineral oil in transformers in 1887, the burgeoning transformer industry had a major problem to solve [1]. As transformers operate, energy losses occur, generating heat. As higher loads are applied, losses increase exponentially, rapidly raising temperatures in a transformer's core and windings. Without adequate cooling, this heat prematurely ages the transformer, ultimately leading to equipment failure. At the time, the only insulating material used was air, but because these first transformers generated high amounts of losses, they were quickly limited in

size by the rapid generation of heat that air failed to properly dissipate [2]. Any attempts at larger devices would fail. Once Elihu Thomson identified oil as a readily available solution, the history of oil as an insulating medium began. Today, several billion liters of mineral oil are used in electrical equipment worldwide [3].

This paper provides a review of the functions of mineral insulating oils, their chemical composition, and production techniques. Emphasis is placed on describing how differences in crude oil source and refining process can impact the final chemical composition of the oil, and therefore its performance in a transformer.

The life of a transformer is inherently linked to the fundamental role of insulating oils to dissipate heat and protect the transformer's solid insulation

2. Functions of a mineral insulating oil

Fulfilling four main functions, insulating liquids are a critical component of power equipment. Originally, the two primary functions of the liquid were to dissipate heat through convection (heat transfer), and to act as an insulating material providing dielectric strength. As testing methodologies and our understanding of oil in transformers developed, a third function grew in importance – that of a diagnostic tool (ex. Dissolved Gas Analysis). Like testing for cholesterol in an individual's blood, measuring and monitoring specific chemical markers in a transformer's oil allows for the early detection of warning signs in a transformer's health.

Somewhat cumulatively, the fourth and most important function of an insulating liquid is to protect the solid insulation. The life of a transformer is inherently tied to the life of its solid insulation. By protecting the solid insulation from oxygen, water, and heat, insulating oils maintain and extend the service life of a transformer. With the majority of the world's transformers advancing in age, and increasing demands being placed on existing infrastructure, the performance demands on insulating liquids have increased.

In urban centers worldwide, transformers are routinely loaded to increasingly higher levels, with less reserve space due to rapid population growth. In these stressed environments, transformers can operate at high load and overload conditions. Removing excess heat and ensuring that the cooling system performs effectively and efficiently is therefore essential to extending the transformer's lifespan, preventing costly failures, and maintaining grid integrity.

Because of the critical role insulating mineral oils play in today's electrical industry, numerous groups have formed to study their electrical, chemical, and physical properties and provide best use recommendations and performance requirements. Standards now exist which dictate specific electrical, chemical, and physical properties. Within North America, the primary standards are developed by ASTM International (ASTM D3487) and the Institute of Electrical and Electronics Engineers (IEEE C57.106). Where ASTM creates and publishes standards on test methods and material specifications, the IEEE interprets the standards into guides applicable to industry needs. Internationally, the International Electrotechnical Commission (IEC) issues its own guide (IEC 60296), with supporting studies conducted by The International Council on Large Electric Systems - Conseil International des Grands Réseaux Électriques, CIGRÉ. Country specific standards also exist. For example, the Canadian Standard Association (CSA-C50) specifies unique viscosity requirements for mineral oils used in cold temperatures (Arctic grade oils).

While these standards represent industry supported guidelines, ultimately, the transformer purchaser has the ability to specify their requirements. Numerous transformer mineral oils are currently available for purchase, produced from differing crude oil sources with varying levels of refinement. Although these different products may meet a standard's requirements, it does not mean their performance is equal. For example, a transformer mineral oil which thickens near and solidifies at -40°C (-40°F) technically meets the same ASTM D3487 requirements as the one which remains flowing until -60°C (-76°F). For a wind farm transformer in North Dakota, the difference is significant. The standards set a threshold for general requirements; however, within their wide breadth fall products with different tiers of quality and performance.

3. Types of mineral insulating oils

Mineral insulating oils used in transformers today are generally produced

Developments in refining technology means that not all mineral oils are equal

from the distillation and refinement of crude oils. As refining technologies have advanced, so too have the resulting mineral insulating oils. The physical, chemical, and electrical properties of a mineral insulating oil are determined by its composition, which varies with the crude oil and refining process employed. Crude oil is a complex mixture of hydrocarbons including normal- paraffins (straight chain hydrocarbons or wax), isoparaffins (branched hydrocarbons), cycloparaffins (saturated ring containing hydrocarbons or naphthenics), aromatics (unsaturated six-membered ring structures), various unsaturated hydrocarbons (containing reactive bonds), sulfur- oxygen-, and nitrogen-containing compounds, as well as metals (Figure 1). Since crude oil reservoirs are found in diverse geographies, one crude oil can differ significantly from another in the relative proportion of each hydrocarbon.

The physical properties of the oils include viscosity (the ability of the liquid to flow), heat capacity (the amount of heat needed to raise the liquid's temperature by 1°C), relative density, flash point (reflecting volatility and combustibility), and thermal conductivity (the rate of heat transfer). These qualities are vital for removing excess heat in electrical transformers. They define the liquid's ability to move through the transformer and its cooling system, draw heat away from sensitive areas (the core and windings), and unload thermal energy into the atmosphere. Since mitigating thermal risk and protecting the paper insulation is the number one function of a transformer insulating liquid, any improvements to these properties confer improvements to the insulating liquid as a whole.

Within the transformer oil industry, two main types of crude oil are relevant: naphthenic (containing <50 % paraffinic hydrocarbons) and paraffinic (containing >50 % paraffinic hydrocarbons) crudes. The general aim of any refining operation is to remove impurities and improve key performance properties of the final material. For mineral oils, this final product is known as a base oil (a transformer mineral oil can consist of up to 100 % base oil). In the early days, refining goals were achieved using acid treatment, clay filtration, and by 1930, solvent refining. In the 1950s, hydrotreating technologies were developed where hydrogen is added to the base oil under elevated temperatures and pressures to break open rings, remove impurities, and saturate reactive bonds. Later advances increased the pressures and temperatures used (severe hydrotreating) to produce purer base oils. From the 1970s - 1990s a number of new base oil refineries were built incorporating a process known as catalytic dewaxing. In this process, wax molecules (normal-paraffins) are catalytically converted to branched hydrocarbons (isoparaffins) with significantly improved cold temperature, viscosity, and oxidative properties. Since no two base oil refineries are alike, a transformer mineral oil produced at one refinery can vary significantly to an oil produced at another using different feeds, refining technologies and operating parameters.

Paraffinic crude oils were originally used as transformer mineral oils, however, due to their high wax content they exhibited prohibitively poor cold temperature properties. In the 1920s, naphthenic oils took their place due to their relatively low cost, low wax content, and availability. Since then, naphthenics have remained the predominant form of mineral insulating oil used in transformers. Petroleum refining, however, has

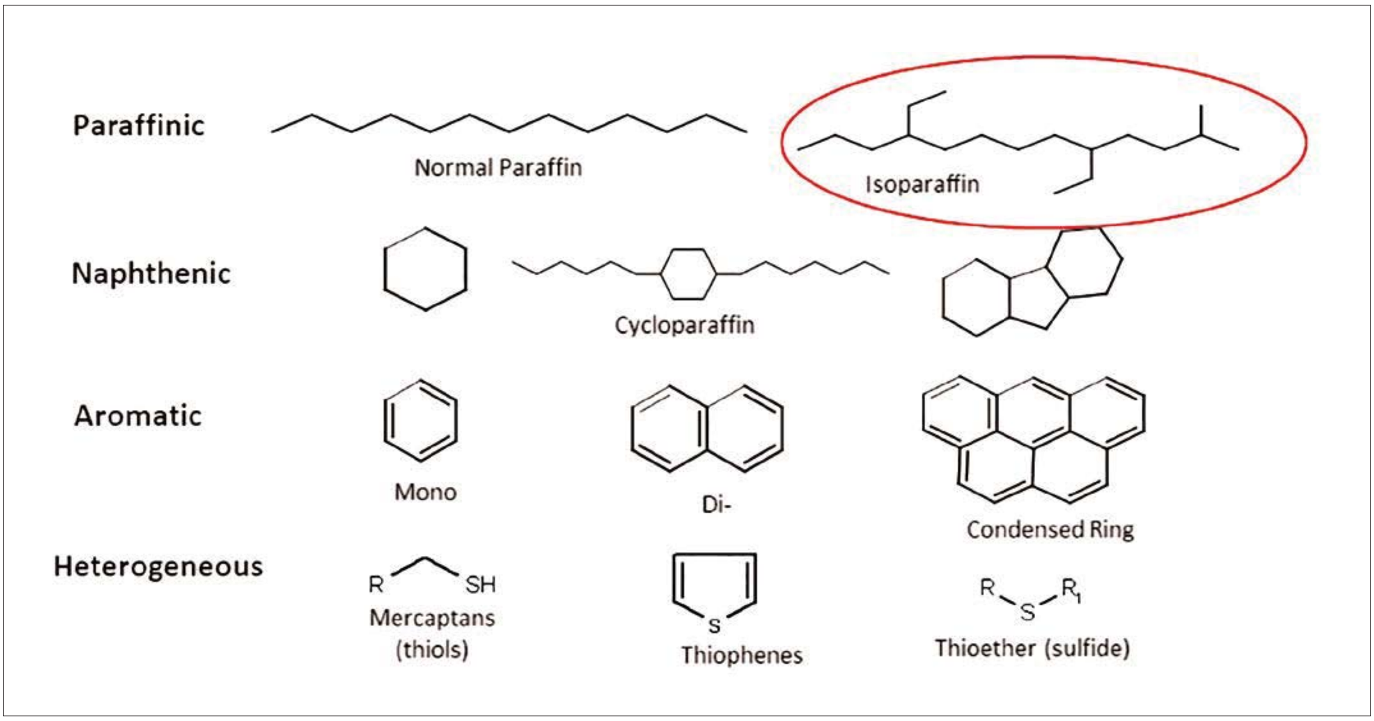

Figure 1. Hydrocarbon species found in crude oil

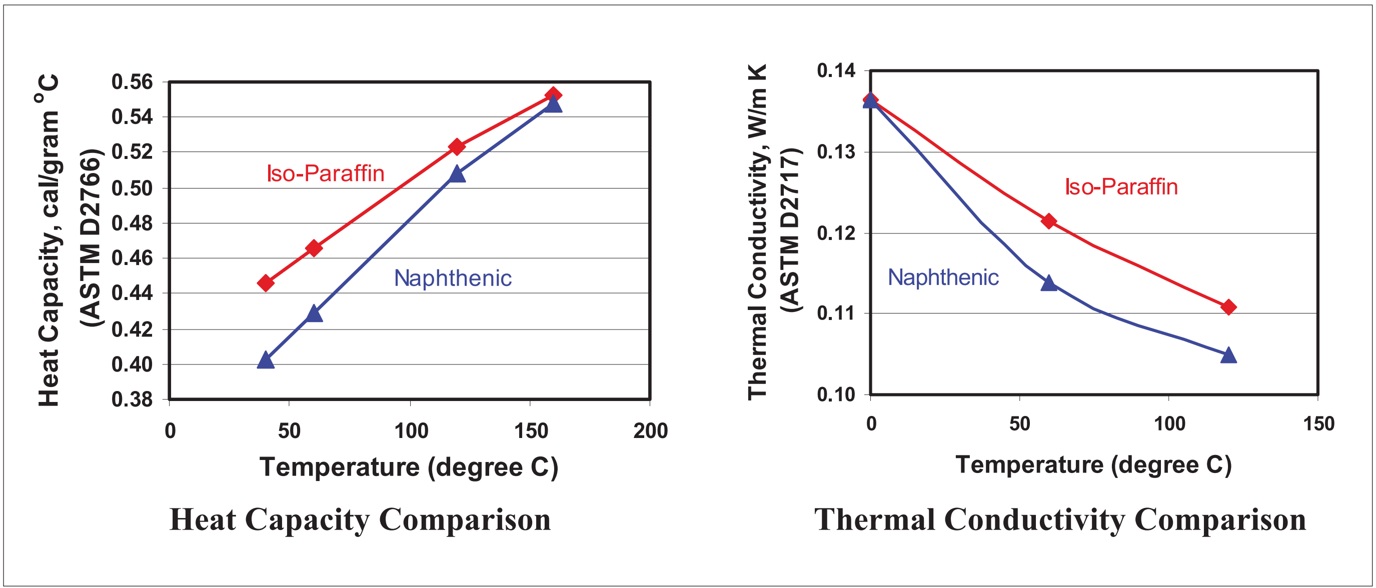

Figure 2. Improved heat transfer capability using isoparaffinic oil versus naphthenic oil [4]

Isoparaffinic oils can offer enhanced oxidative stability, lower viscosity in colder temperatures, and superior heat transfer which results in improved reliability and utility for transformer operators

changed dramatically since the 1920s. Naphthenic oils are typically manufactured using solvent refining followed by mild hydrotreating. This can leave residual compounds in the oil including aromatics and reactive sulfur- and nitrogen-containing compounds. Sulfur specifically has been a concern for its corrosive effects on copper windings. Isoparaffinic oils are highly refined using newer severe hydrotreating (3000 psi, 750°F / 399°C) and catalytic dewaxing technologies. They contain almost no contaminants and are free of any detectable sulfur. Furthermore, a number of recent studies have shown isoparaffinic oils also offer desirable heat transfer, cold temperature, oxidative stability, and density properties.

4. Isoparaffinic oils in practice

The heat transfer performance of naphthenic and isoparaffinic mineral oils can be seen in Figure 2 [4].

In laboratory testing, isoparaffins offer higher heat capacity and thermal conductivity than naphthenic oil. In practice, this means the isoparaffinic oil would run cooler than its naphthenic counterpart if the same level of heat was generated in the windings and core. In addition, due to its higher thermal conductivity, the liquid will transfer heat from the hot coils to the outside air much quicker. With improved heat transfer, a transformer can decrease usage of its cooling pumps and fans.

To test this principle, Cinergy Substation Services (now owned by Duke Energy) conducted a study consisting of three separate tests: a heat run, a retro-fill comparison in the same in-service transformer, and a side-by-side comparison with in-service transformers [1].

The heat run test involved two newly manufactured matching transformers that had a high side winding voltage of 67 kV and a low side winding voltage of 13.09 kV. One transformer was filled with an isoparaffinic transformer oil and the other used a mixture of naphthenic oils. With all other variables being equal, results showed the isoparaffinic oil had a 6.5 -8.5 % heat transfer coefficient advantage over the naphthenic oil.

The next test used an in-service 1971 model transformer that had five years of operating data using a naphthenic oil. During those five years, the top oil temperature was on average 41.3°C higher than ambient temperatures. By draining the transformer and refilling it with an isoparaffinic oil its performance could then be compared over time. The results showed that over the course of a year, with an isoparaffinic oil, the transformer averaged a top oil temperature 34.6°C over ambient. By running at 6.7°C cooler than the naphthenic oil, the transformer was calculated to have an additional 8.0 % load availability.

The final test of the study was the most compelling as three identical transformers were set in parallel and exposed to the same environmental conditions. The first transformer used an isoparaffinic oil, while the two remaining units utilized naphthenic oils. The test again concluded that by using an isoparaffinic oil with better heat transfer capability, a greater load could be applied to the transformer before hitting the rated temperature limits.

Adding to these results, a later study sought to examine the performance of isoparaffinic oils under accelerated aging conditions [5]. In this study, 10 kV

Using an isoparaffinic oil in a transformer creates the potential for increased load before hitting the upper rated temperature limit for the unit

distribution transformers were filled with either an isoparaffinic oil, a naphthenic oil, or a combination of the two. It should be noted that since both types of oils are derived from petroleum, they are fully compatible and miscible. The transformers were then operated under high load (115°C / 239°F top oil temperature) or overload conditions (135°C / 275°F top oil temperature) for 4000 hours.

During this study a transformer containing the isoparaffinic oil ran approximately 5°C cooler than a naphthenic alternative in overload conditions. One (of two) naphthenic oils aged so rapidly that the transformer's paper insulation crumbled upon inspection. This observation reinforces the diversity that exists even between naphthenic oils and the importance of proper oil selection.

Another benefit of isoparaffinic oils is their unique response to antioxidants leading to exceptional oxidative stability. As an oil ages it oxidizes producing acidic molecules and sludge; this lowers its dielectric strength, increases its viscosity, and ultimately, limits its effectiveness to protect the solid insulation. Knowing the importance of oxidative stability the ASTM standard for insulating mineral oils (ASTM D3487) sets a threshold value using test method ASTM D2112 (RPVOT), where a sample of oil is placed in a pressurized vessel under high temperatures and the amount of time required for the oil to breakdown is measured in minutes. Figure 3 shows the range of ASTM D2112 results seen across a selection of oils and highlights the oxidative stability of isoparaffinic oils. To test whether the superior oxidative stability of isoparaffinic transformer oils could improve the aging properties of a conventional transformer oil, mixtures of the two products in various proportions were tested for various electrical and chemical properties.

Figure 4 shows that even a 5 % addition of an isoparaffinic oil can improve power factor and oxidative stability properties.

In a further study, the dangers of a prematurely aging oil were highlighted by a rapid degradation in color, dissipation factor, acid number, and interfacial tension, which ultimately lead to thermal degradation and failure of some transformers after only 10 years in service [6]. By switching to an isoparaffinic oil, the transformer operators saw virtually no signs of ageing, with no significant changes in color, dissipation factor, acid number, or interfacial tension after more than 14 years of service.

For electric transformers operating in the globe's colder regions, isoparaffinic oils can offer improved reliability with the lowest cold temperature viscosities available in the market [4]. For example, one product offers a typical viscosity of 1230 cSt at -40°C / -40°F and a pour point of -60°C / -76°F. While many of today's naphthenic oils have significantly improved pour points, their viscosities still trend higher, ranging from 2000 to > 4000 cSt at -40°C / -40°F. This helps to avoid the thickening of liquids that can occur in cold temperatures and prevent the effective circulation of the transformer oil. Lower viscosities improve the liquid's flow and allow for safer start-ups in cold environments. For transformers with variable loads in cold climates (ex. wind farms), this improved pumpability can significantly improve the transformer's reliability. Cold temperature viscosity is also critical for tap-changers in cold climates to ensure proper functioning of the spring-driven diverter switch [7].

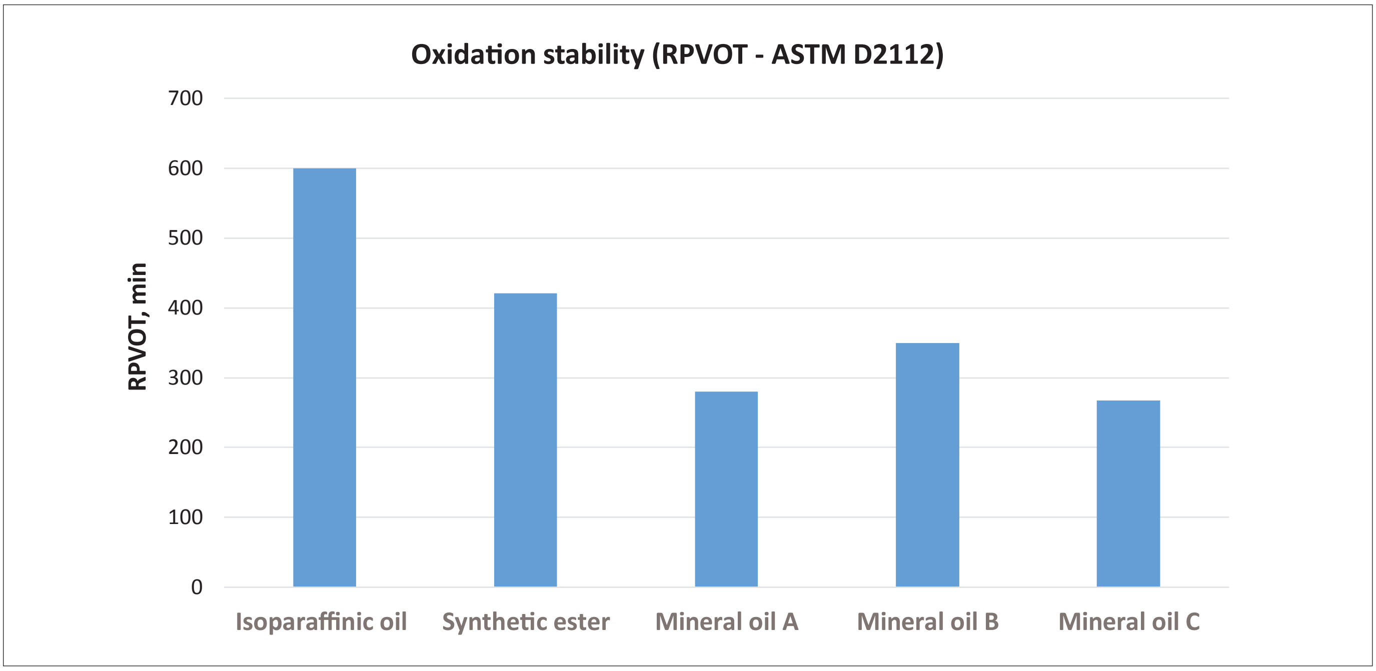

Figure 3. Oxidative stability of transformer mineral oils from different suppliers

% LUMINOL TR % Conv Oil	0 % 100 %	5 % 95 %	25 % 75 %	50 % 50 %	75 % 25 %	95 % 5 %	100 % 0 %
D2440 – Oxidation Stability @ 72 hours % sludge	0.05	0.04	0.01	<0.01	<0.01	<0.01	<0.01
Neut. No, mg KOH/g	0.27	0.24	0.18	<0.01	<0.01	<0.01	<0.01
D2440 - @ 164 hours % sludge	0.10	0.09	0.07	0.03	<0.01	<0.01	<0.01
Neut. No, mg KOH/G	0.31	0.30	0.26	0.17	<0.01	<0.01	<0.01
D924 – Power Factor (%) @ 25°C @100°C	0.042 0.856	0.012 0.354	0.012 0.321	0.013 0.350	0.010 0.163	0.004 0.110	0.007 0.086
D2112 – Rotating Pressure Vessel Oxidation Test (min.)	187	201	217	225	270	353	412

Figure 4. Influence of addition of an isoparaffinic oil on properties of a conventional transformer oil

The isoparaffinic oil would be noticeably cooler than its naphthenic counterpart if the same level of heat was generated in the windings

Finally, the lower density of isoparaffinic oils is advantageous for the overall transformer weight (less mass for the same volume). This property decreases pad requirements, and recently has been a significant benefit for mobile substations. Since isoparaffinic mineral oils are 7 % less dense than the average naphthenic oil, they are much lighter to transport. For a 45 MVA mobile transformer with 41640 L (11,000 gallons) of mineral oil, an isoparaffinic oil can reduce its load weight by approximately 1970 kg – a significant amount when transportation costs are considered, and the Department of Transportation requirements need to be met.

Conclusion

Although mineral insulating oils are required to meet certain specifications, no two mineral oils are exactly alike. The fundamental roles of insulating oils in dissipating heat and protecting the transformer's solid insulation haven't changed since 1887, but today's mineral insulating oils have evolved alongside advances in refining technology.

Differences in chemical (ex. oxidative stability), electrical (ex. dielectric breakdown), and physical (ex. viscosity) properties exist, reflecting the diversity in crude oil origin and the refining process used by different refineries. It is the responsibility of the transformer purchaser to understand that these differences exist and to ensure the best possible liquid is used for their transformer. Offering enhanced oxidative stability, lower viscosity in colder temperatures, and superior heat transfer, the use of isoparaffinic oils can offer improved reliability and utility for transformer operators, while also generating significant life-time cost savings.

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