Electrical Insulating OILS

Herbert G. Erdman

editor

STP 998

ASTM

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ASTM
1916 Race Street
Philadelphia, PA 19103

ASTM Publication Code Number (PCN): 04-998000-21
ISBN: 0-8031-1179-7

Peer Review Policy

Each paper published in this volume was evaluated by three peer reviewers. The authors addressed all of the reviewers' comments to the satisfaction of both the technical editor(s) and the ASTM Committee on Publications.

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Printed in Ann Arbor, MI
September 1988
Second Printing, Ann Arbor, MI
May 1992
Third Printing, Ann Arbor, MI
December 1996

Foreword

This publication, *Electrical Insulating Oils,* contains papers presented at the symposium of the same name held in Bal Harbour, Florida on 19–20 Oct. 1987. The symposium was sponsored by ASTM Committee D-27 on Electrical Insulating Liquids and Gases. Herbert G. Erdman, PSE&G Research Corp., Maplewood, NJ, presided as symposium chairman and was editor of this publication.

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Overview

This symposium was organized to update information on the important role of petroleum-based oil as an insulating and heat transfer agent in electrical apparatus.

The properties of these insulating oils are of vital importance to the service life of electrical equipment and have become increasingly important as operating voltages have increased to 500 kV and above and internal equipment spacings have decreased. The papers in this symposium have been directed towards the changing requirements of the insulating media as demanded by the changing design of the equipment, and they are of particular value to three main groups: the refiners of the oil; the manufacturers of the electrical equipment; and the end users (principally the electric utilities).

The papers in this book address the factors involved in the manufacture and use of the product that will meet these stringent requirements.

From the refiners' standpoint, the papers discuss how the crude oil is selected and what must be done to produce an end product with high dielectric strength, heat transfer capability, low-temperature pour point, resistance to oxidation, and long service life. These factors determine the specifications of the product.

From the users' standpoint, the papers discuss the significance of these specifications and test methods to determine if the specifications have been met, as well as tests to check the condition of oil after use in the equipment. Included is the very important diagnostic test for electric equipment in service, the analysis of dissolved gases in the oil.

Of special interest is section 5, which is devoted to a relatively new problem caused by electrostatic charges built up in the oil due to forced cooling in large transformers.

This volume is of value to all who refine or use insulating oils because it addresses the latest technologies involved.

The first section of this book, "Refining and Specification Limits," addresses methods used in refining crude oil to produce a product which is suitable for both electric insulation and heat transfer. Included is the problem of handling and shipping the product once produced. Contamination can occur from tank cars and drums that are not completely devoid of foreign materials or not properly sealed. The paper by Manger, which discusses cross contamination with polychlorinated biphenyls (PCB), is included to describe a specific problem. This paper updates the local and federal regulations dealing with PCB contamination.

The second section, "Significance of Application," addresses the reasons behind the various specifications for insulating oils and the significance of these specifications to the users.

The third section, "Analysis of Oil," discusses the methods of analysis to determine if these specifications have been met. There are two conditions to be considered: (1) analyzing new oil as shipped; and, perhaps more important, (2) the analysis of oil after certain periods of time in the electrical equipment to determine deterioration and predict further usefulness of the oil.

The fourth section, "Dissolved Gas in Oil," discusses the analysis of gases dissolved in oil and the significance of various gases to the condition of the electrical equipment involved. This is a very useful diagnostic test, particularly to monitor the performance of large high-voltage transformers.

The fifth section, "Electrostatic Buildup in Transformer Oil," perhaps one of the most provocative, has to do with a recent problem that has arisen in large transformers where the pumping of the oil is required to limit the temperature rise in the transformers. Pumping a liquid with high dielectric strength and very low quantities of moisture over various materials in the pump and in the insulating material, in many cases, has caused an electrostatic charge buildup in the oil and has resulted in electrical failure in several large transformers throughout the country. The papers in this section present the latest information on this phenomena. There is much more to be learned of this complex process, and much work is being done throughout the country to try and solve this problem.

The papers in this book should provide the reader with the latest technologies in selecting and handling this very important insulating media for electric equipment. This is a very significant area for equipment designers. Large capacity size and weight of electrical equipment is of vital importance, resulting in smaller internal spacings requiring the best dielectric material available.

ASTM Committee D27 on Electrical Insulating Liquids and Gases is continually working to update this material, improve test procedures, and investigate newly refined products that appear on the market. Refiners are continuously producing new insulating oils from petroleum crude oil. In addition, manufacturers are continually producing synthetic insulating fluids. Committee D27 on Electrical Insulating Liquids and Gases addresses these new products as they come on the market.

Herbert G. Erdman,

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Section I—Refining and Specification Limits

Thomas G. Lipscomb, II[1]

Mineral Insulating Oil Manufacture and Safekeeping

REFERENCE: Lipscomb, T. G. II, **"Mineral Insulating Oil Manufacture and Safekeeping,"** *Electrical Insulating Oils, STP 998,* H. G. Erdman, Ed., American Society for Testing and Materials, Philadelphia, 1988, pp. 5-24.

ABSTRACT: This paper presents a general overview of the methods used to refine conventional mineral insulating oils. The discussion will outline the individual refining processes and the effect each may have on the composition of the oil. Included will be a brief discussion of the Occupational Safety and Health Administration's Hazard Communication Standard, 29 CFR 1910.1200 as it can apply to mineral insulating oil and some suggestions for handling and storage of the oil to reduce contamination and degradation.

KEY WORDS: transformer oil, mineral insulating oil, refining, naphthenic transformer oil, paraffinic transformer oil, storage, handling, cancer hazard warning, OSHA hazard communication standard

In planning a seminar on the subject of insulating oil of petroleum origin, it was recognized that many people involved in using "mineral insulating oils" or "transformer oils" have probably never known how they are made. Only those persons involved in their manufacture or in research on the subject have direct knowledge.

The author was asked to provide information of a nonproprietary nature on the general subject to serve as a basis for understanding some of the properties of transformer oils that will be discussed in subsequent papers.

Discussion

Refining

Mineral transformer oil today is a compromise between what is needed by the equipment, what is desired by the customer, and what can be achieved without overwhelming complexity in the refining process. This compromise is well exemplified by ASTM Specification for Mineral Insulating Oil Used in Electrical Apparatus (D 3487). The need to meet this specification in the most efficient manner is the aim of the refiner.

The manufacture of transformer oil begins with a choice of crude oil type: naphthenic, paraffinic, or mixed base. Convention in the United States has been to use naphthenic crudes, since they generally contain very much lower concentrations of n-paraffins (wax), and the resultant product has a low pour point without dewaxing being required. This convention at one time applied everywhere, but necessity has driven some regions of the world to use mixed-base or paraffinic crudes as sources. All useable lube crudes can be manipulated by suitable combinations of processes to result in a useable transformer oil. The degree of difficulty in refining and the product yield will vary with the crude.

There is also another little-appreciated benefit of using naphthenic oils; their viscosities change much faster with temperature than those of paraffinic-derived oils. Normally, this might

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be considered a detriment, but not in this case. As the temperature rises in a transformer, the oil becomes less viscous and the heat transfer rate is improved. For oils of equal viscosity at 40°C, the heat transfer coefficient can be as much as 8 to 11% greater at 100°C for an oil of 30 VI (viscosity index) versus an oil of 100 VI.

Since the world supply of good "low cold test" naphthenic crudes has declined, we have seen paraffinic crudes being used as sources, particularly in South America, Mexico, and Europe. One such oil was commercially introduced in the United States. At the time this paper was written, it was withdrawn from the market.

The definition of a naphthenic crude by the U.S. Bureau of Mines contains no mention of the pour point of the distillate nor of the n-paraffin content. This classification system is shown in Fig. 1. By this system it is possible to have nine different crude types, depending upon the various combinations of light key and heavy key classifications.

ASTM Committee D27 was more pragmatic and chose to use the definitions in ASTM Definitions of Terms Relating to Electrical Insulating Liquids and Gases (D 2864) as shown in Fig. 2. Although not technically correct, they represent the main concerns about pour points, low-temperature viscosities, and the means needed to achieve the desired properties.

Refining processes are used to eliminate undesirable compounds and to retain those that are desirable. The elimination procedure may be by simple removal or by conversion to more desirable compounds. Both types of elimination procedures are represented by refining processes commonly in use today.

Crude Distillation

The first step in producing a transformer oil is distillation of the crude to produce a suitable distillate feedstock. This is usually done on a pipe still. The distillate can be taken as a side stream product from either the atmospheric tower or the vacuum tower. Or a very broad stream can be taken, processed partially, and then redistilled to the desired narrow boiling range. Figure 3 shows a schematic flow diagram of a typical pipe still operation.

In this process, "light ends" are removed in a prefractionator tower (distillation column) not shown in the diagram, and "middle distillate" type products are removed in the atmospheric tower. The "reduced crude" from the bottom of the atmospheric tower then goes to the final, or vacuum, tower. This distillation column is run under vacuum to keep the boiling point of the individual fractions well below the cracking temperature, that is, the temperature at which thermal decomposition of the oil molecules would begin. Cracking of hydrocarbons usually becomes rapid enough to detect at about 370°C (700°F).

Steam is usually added to the bottom of the vacuum tower to further lower hydrocarbon partial pressure and reduce the temperature required for distillation still more. The transformer oil distillate, being relatively low boiling, is removed near the top of the tower. As mentioned earlier, the transformer oil distillate could also have been removed as a lower side stream on the atmospheric tower.

A question sometimes asked is, "What portion of crude can be made into transformer oil?"

	Gravity of Key Fraction, °API	
	Light Key Fraction (482-527°F)	Heavy Key Fraction (740-790°F)
Paraffinic	>40	>30
Intermediate	33-40	20-30
Naphthenic	<33	<20

FIG. 1—*Crude oil classifications (U.S. Bureau of Mines).*

Naphthenic Oil

A term applied to mineral insulating oil derived from special crudes having very low, naturally occuring n-paraffin (wax) contents. Such an oil has a low natural pour point and does not need to be dewaxed nor does it usually require the use of a pour depressant.

Paraffinic Oil

A term applied to mineral insulating oil derived from crudes having substantial contents of naturally occurring n-paraffins (wax). Such an oil must be dewaxed and may need the addition of a pour depressant in order to exhibit a low pour point.

FIG. 2—*Definitions of naphthenic oil and paraffinic oil.*

For most useable crudes, the distillate yield can be from 3 to 10% of the whole crude. There are two limiting factors. On the front end, the flash point limits the amount of light molecules that can be present. The second limitation is the maximum viscosity. As increasing amounts of heavier molecules are included, the viscosity of the whole fraction increases until the specified limit is reached.

There are other practical considerations. The molecules boiling above and below the desired fraction are valuable for other uses. Pipe stills are not perfect; there is overlap between fractions. If the maximum amount of transformer distillate is taken, then a shortage of the next lower and/or higher boiling fractions may develop.

In looking at some current typical transformer oils versus ASTM D 3487, none seems to be at the minimum flash point, and none is at the maximum viscosity, so compromise has won again.

Table 1 shows the boiling range of a distillate from a naphthenic crude and one from a paraffinic crude [by ASTM Test Method for Boiling Range Distribution of Petroleum Fractions by Gas Chromatography (D 2887)]. Both distillates were used to make finished transformer oil.

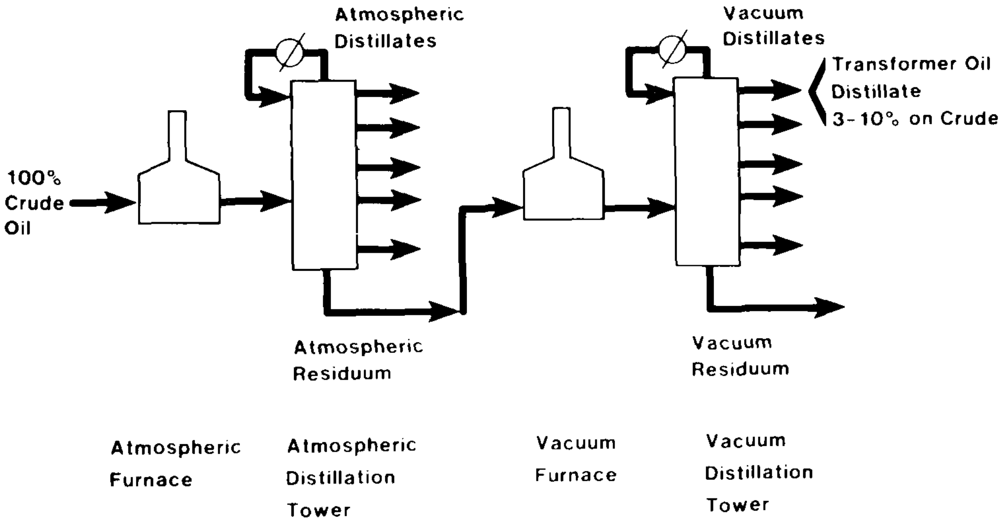


FIG. 3—*Distillation to make transformer oil base stock.*

TABLE 1—*Comparison of naphthenic and paraffinic distillates boiling ranges.*

	Naphthenic	Paraffinic
Initial boiling point, °C	283	239
5% distilled, °C	271	306
50% distilled, °C	330	372
95% distilled, °C	384	419
Final boiling point, °C	429	531

The data for the naphthenic distillate can be translated into an average molecular weight of 255, or an average molecule with 18 carbon atoms (carbon number = 18), if all of the compounds were paraffins. Similarly, the molecular weight of the paraffinic distillate would be about 300.

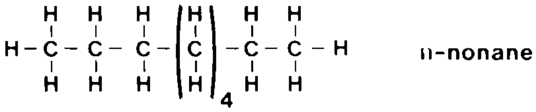
Not all of the compounds present in naphthenic distillates are paraffins, far from it. There is a great variety of compounds present, and, in general, the same types of compounds are present in all crudes. The difference in crudes can be found in the relative amounts of the various compound types and in the degree and kind of substitution on the ring structures.

Molecular Components of the Distillate

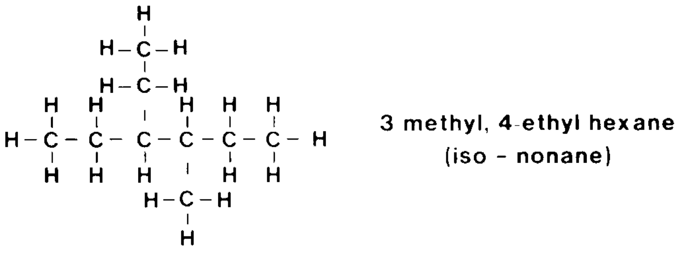
Before examining the next processing steps, we need to illustrate the various molecule types present in the distillate. Refining is essentially the effort to remove or preserve these compounds.

Paraffins, normal-, iso-, and cyclo-, are shown in Figs. 4 and 5. Remember, we said that the average carbon number was 18, yet the structures shown do not have 18 carbons. We are illustrating the compound types present, not the actual compounds themselves in order to simplify the drawings.

A naphthenic crude-derived distillate will have very low n-paraffin content. There will be some present, but the values will be so low as to be almost unmeasurable. Not all naphthenic

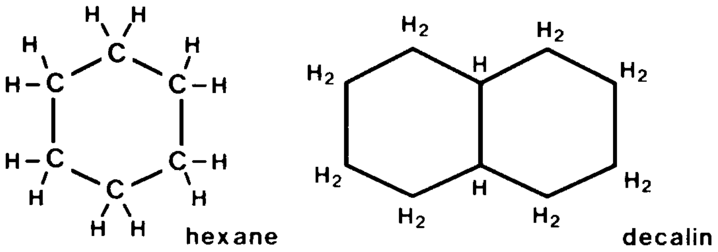


Normal-Paraffin



iso - Paraffin

FIG. 4—*Paraffins.*



1 - Ring Naphthene (cyclo-Paraffin)

2 - Ring Naphthene

FIG. 5—*Naphthenes.*

crudes are wax free. There are some which meet the U.S. Bureau of Mines definition, but which contain enough wax to make them unsuitable for "low cold test" products.

The naphthenic distillate will then contain considerable amounts of iso-paraffins and cyclo-paraffins. The iso-paraffins have very low crystallization temperatures, as do the cyclo-paraffins, provided that they do not have very long n-paraffin side chain substitutions. All these cyclo-paraffins, also called naphthenes (hence the name naphthenic crude), will have some substitution of side chains, probably several short or branched chains.

We want to keep the iso-paraffins and cyclo-paraffins and, if necessary, reject n-paraffins.

Olefins are shown in Fig. 6. The double bond makes them highly reactive to form sludges, acids, aldehydes, etc. There are several ways to eliminate them, which will be discussed later.

Aromatics are a major constituent of the distillate. Figure 7 does not show any side chain substitution, but at this boiling range all of the aromatics present will have side chains. The degree and kind of substitution strongly affects the viscosity/temperature properties of these aromatics. Note also mixed molecules, naphtheno-aromatics, where part is aromatic and part is naphthenic. Indane is an example.

Aromatics are both good and bad. We need to keep some but not all. In general, as the aromatic content is decreased, the gassing tendency of the oil increases, and the impulse

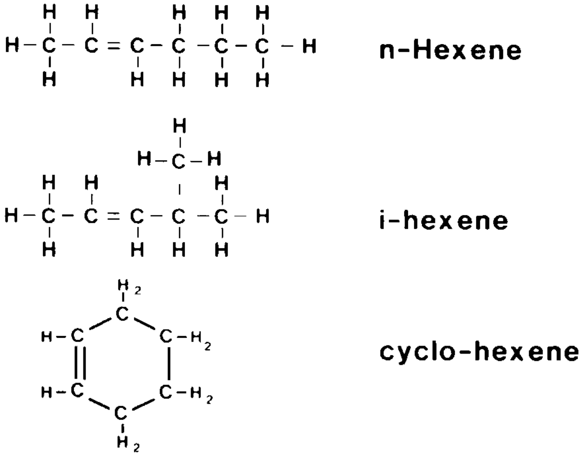


FIG. 6—*Olefins.*

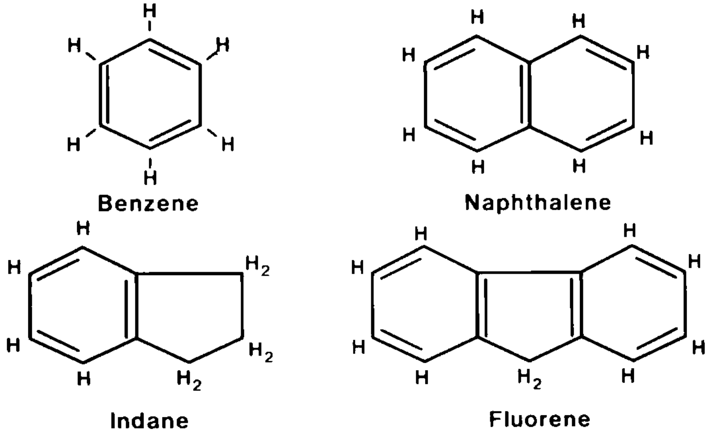


FIG. 7—*Aromatics.*

strength goes up. Also, some aromatics seem to be mild oxidation inhibitors. The refiner must then try to remove some aromatics, leave some aromatics, be selective about the process, and compromise between the desire for good antigassing properties, good impulse strength, and good oxidation resistance.

Polar compounds, and there are many types, are shown beginning in Fig. 8. Heterocyclic aromatics containing nitrogen or oxygen are generally undesirable. They are not stable as to oxidation, color, etc. Thiophenes may be an exception. Certain thiophenes are known to be moderate oxidation inhibitors.

Polar oxygenates shown in Fig. 9 are all undesirable. If they are not already, they soon will degrade further to become acids. As acids they contribute to corrosion, low interfacial tension, and poor dissipation factor.

Sulfur compounds, except for thiophene, are shown in Fig. 10. Some of these may be mild antioxidants, but they also react with copper and have objectionable odors. These compounds must be removed.

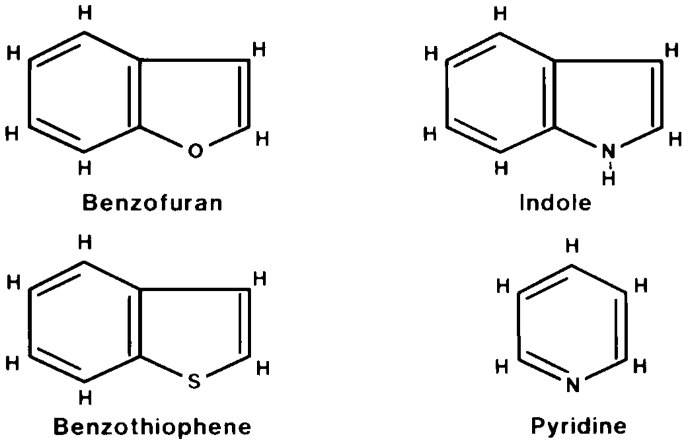


FIG. 8—*Polars, heterocyclics.*

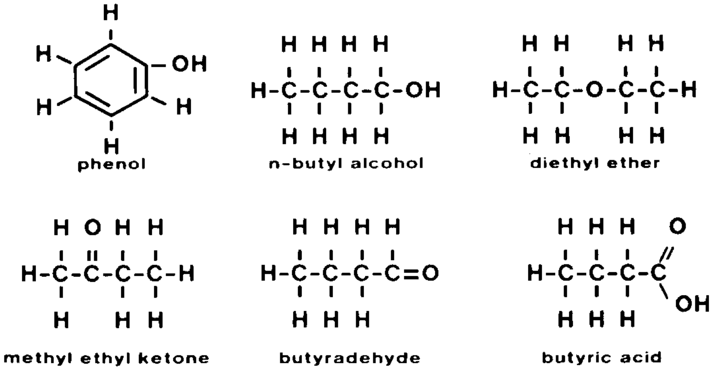


FIG. 9—*Polars, oxygenates.*

Actually, there are two more ever-present materials we must consider: water and particulates. These must be removed because they are as deleterious to the performance of the finished oil as any of the molecules previously mentioned.

Refining the Distillate

In this section we will describe each of the major refining processes. In a later section we will compare the physical and chemical effects of the processes on each molecule type present in the distillate. In examining the refining processes, it is well to keep in mind that it is rare to find a single process that will do all. Combinations of processes are the rule. We will list some of the more popular combinations, but not by any means all combinations.

Acid Treating—The first refining process is acid refining or acid treating. Many years ago it was the "one" accepted method, but in reality it was a dual process, for it was combined with clay treating. Figure 11 shows a block diagram of the process.

In this process, the transformer oil distillate is initially contacted with 90 to 99% sulfuric acid. A very light treat, 2 to 4 volume % acid based on the distillate, is used. The contact time of acid and distillate varies between about 0.1 and 4 s. Following mixing, the acid sludge that is formed from the chemical reaction of acid and oil is separated from the oil by centrifuging. At this point some harmful sulfonic acids and nitrogen bases are removed as sludge from the oil.

The oil from the centrifuging operation contains oil-soluble acidic compounds resulting from the reaction with sulfuric acid. Upon neutralization with sodium carbonate or caustic soda and

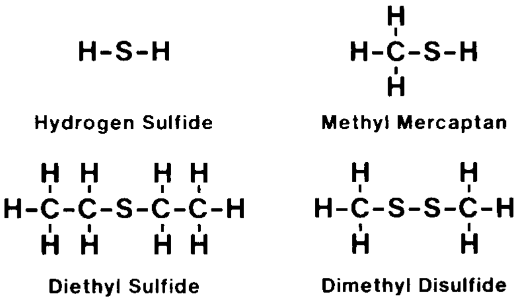


FIG. 10—*Sulfur compounds.*