

Historical evolution of organic and insulating liquids

From whale oil to mineral and vegetable oil

ABSTRACT

Vegetable oils, although recognized early for their insulating potential, were largely dismissed as transformer-insulating liquids during the formative years of electrical engineering. This column explores the technical and historical reasons behind the preference for mineral oils over vegetable oils 100 years ago, analyzing early research findings and practical considerations. Key aspects such as oxidation stability, moisture absorption, low-temperature performance, gas absorption, and material consistency are examined alongside the technological limitations of the early 20th century. The timeline of the appearance and disappearance of various animal, vegetable and mineral oils is also detailed. A brief, non-chemist explanation of the molecular structure differences between esters and mineral oils is also provided.

KEYWORDS:

mineral oil, vegetable oil, natural esters, synthetic esters, oxidation stability, moisture absorption, biodegradability, dielectric properties, dire safety



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Introduction

The use of insulating liquids is vital for transformer performance, providing dielectric insulation and thermal management. While vegetable oils were among the first insulating materials investigated, mineral oils quickly became the industry standard.

It is important to note that not all insulating liquids are created equal, and not every claim withstands real-world scrutiny. A critical evaluation of the insulating fluids emerging in the 21st century highlights significant differences in reliability, fire safety, environmental impact, and operational performance. Rather than focusing on chemical intricacies, the forthcoming

analysis will emphasize practical outcomes and long-term implications for transformer operation. Key aspects to be examined include the comparative carbon footprint of mineral oils versus vegetable-based esters, biodegradability and behavior in real-world spill scenarios, fire resistance characteristics, aging tendencies under electrical and thermal stress, and maintenance considerations over the service life. In an increasingly complex market, a clear understanding of these factors is essential for making informed, sustainable transformer fluid selections.

This column analyzes why vegetable oils were not widely adopted during the early development of power transformers.

Timeline of organic and insulating liquid development

- 1000–1700: Use of animal fats (especially whale oil) for lighting and lubrication [10].
- 1850s: Whale oil scarcity emerges; prices rise dramatically [10].
- 1859: Discovery of petroleum and beginning of commercial oil refining in Titusville, USA [10].
- 1860s–1870s: Early mineral oils developed and gradually replaced whale oil in industry [10][2].
- 1880s: Initial experimental uses of vegetable oils for lubrication and insulation [5][6].
- 1890s: Patents filed for the use of min-





- eral oils in electrical transformers [2].
- 1900–1930s: Mineral oils become the global standard for transformer insulation; vegetable oils trialed but largely abandoned [2][5].
- 1970s–1990s: Environmental concerns about mineral oil spills led to renewed research into alternative liquids [7].
- 1990s–2020s: Natural and synthetic esters have become established alternatives to mineral oil, particularly in applications demanding high fire safety or environmental compatibility (e.g., indoors, tunnels, offshore wind turbines). Commercial products emerge in quite large numbers for both natural and synthetic esters, based on the variance of sources, formulations, additives and accumulated experience. Standard test methods initially adapted from mineral oil standards, have been developed specifically for esters (e.g., ASTM D6871 for natural esters). Research continues to focus on optimizing ester performance through advanced additive packages, understanding long-term

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aging behavior, exploring novel sources, and investigating performance enhancements via nanoparticles. The unique interaction between esters and cellulose, particularly the ability of natural esters to absorb moisture and potentially extend paper life through hydrolysis, is a key area of study [1][7][9].

Chemical structure differences: Esters vs mineral oils

Mineral oils are mostly made of hydrocarbons, which are chains of carbon

and hydrogen atoms, much like gasoline or diesel. They are chemically simple, non-polar, and relatively stable but can oxidize slowly over time.

Natural esters, by contrast, are molecules built from a backbone called glycerol, bonded to three fatty acid chains. Think of it like a three-pronged fork holding organic “arms”. These “arms” often have double bonds (unsaturations) that make esters more chemically active. While this structure gives esters environmental benefits (biodegradability and high fire point), it also makes them more sensitive to oxygen and moisture without protection.



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Property	Mineral Oil	Natural Ester	Synthetic Ester
Source	Petroleum	Vegetable Seeds	Chemical Synthesis
Chemistry	Hydrocarbons	Triglycerides	Polyol Esters
Biodegradability	Poor - Moderate	Good*	Good *
Flash Point (°C)	>145	>300	~250-270
Fire Point (°C)	~180	>300	~300-310
Pour Point (°C)	<-40	-12 to -31*	-40 to -60
Viscosity @ 40°C (cSt)	≤11	~30-40*	~14-29
Relative Density	<0.91	~0.92	~0.9-1.0
Dielectric Constant	~2.2	~3.1-3.3	~3.0-3.5
Water Solubility	Low (~50ppm @ 25°C)	High (~1100ppm @ 25°C)	Moderate-High
Oxidation Stability	Good - Moderate (inhibited)	Variable (requires AO) †	Good (often inhibited)
Hydrolysis	N/A	Occurs (dries paper)	Occurs

*Properties depend significantly on the specific vegetable source and additives (e.g., pour point depressants). †Highly dependent on fatty acid profile; requires antioxidants (AO) for stability and oxygen availability dependence.

In simple terms:

- Mineral oils are like long, simple ropes, sturdy but less eco-friendly.
- Natural esters are like more intricate branches, flexible and green, but they need care to avoid fast decay.

Synthetic Esters: Typically, polyol esters, such as pentaerythritol tetraesters. Formed from an alcohol base and selected (often saturated) carboxylic acids. Possessing multiple polar ester groups but lacking the C=C double bonds found in many vegetable oils, contributing to good oxidation stability. Synthetic esters are biodegradable.

These chemical differences translate into distinct physical, chemical, and electrical properties:

Those are the main properties the natural ester liquids were rejected for being used at the beginning of the 20th century:

1. Oxidation stability

Early investigations highlighted the severe oxidation tendencies of vegetable oils when exposed to air (Figure 1). Oxidation led to the rapid formation of acids, sludge, and polymerized materials, severely degrading insulating properties and accelerating solid insulation aging. Castor oil and linseed oil, for instance, quickly developed gels upon air exposure. In contrast, mineral oils, though also prone to oxidation, demonstrated significantly greater oxidative stability under similar conditions [2][5].

2. Moisture absorption

Vegetable oils such as castor oil, coconut oil, and olive oil are hygroscopic, absorbing ambient moisture far more readily than mineral oils. Table 1. High moisture content lowers dielectric strength and accelerates chemical degradation. During the early 20th century, free-breathing transformer designs lacked effective moisture barriers, making vegetable oils particularly unsuitable [3].

3. Poor low-temperature performance

Vegetable oils generally exhibit higher pour points compared to mineral oils.

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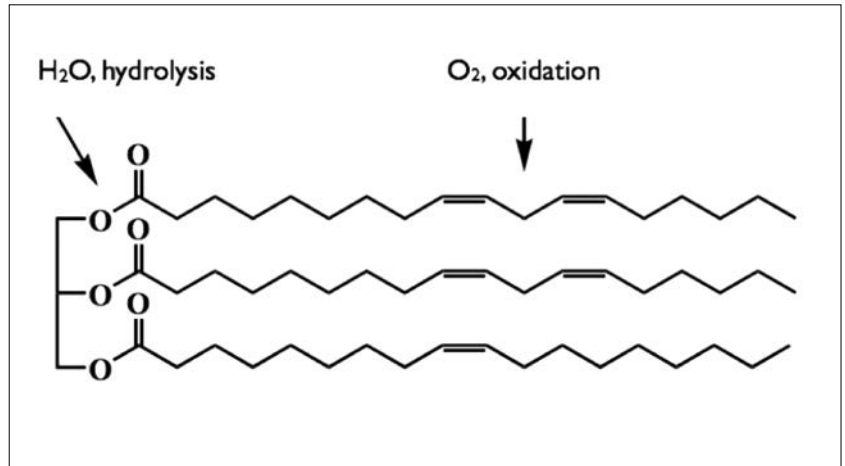


Figure 1. Two of the three scenarios of degradation of natural esters

Table 1. Water max solubility for mineral oil, synthetic ester and natural ester

	Ester linkages	Approx water saturation at 23°C (ppm)	Approx water saturation at 60°C (ppm)
Mineral oil	0	55	120
Silicone oil	0	220	800
Natural ester	3	1100	2000
Synthetic ester	4	2600	5000

The inconsistency in vegetable oil quality made standardization difficult, unlike mineral oils, which could be more uniformly refined and tested for transformer applications

For example, castor oil and sesame oil solidify at relatively high temperatures compared to refined mineral oils. Their tendency to become viscous or semi-solid at lower temperatures limited their effectiveness as coolants and dielectric materials, particularly in colder climates. Therefore, mineral oils with lower pour points performed reliably across wider temperature ranges [4].

4. Variability and lack of standardization

The chemical properties of vegetable oils, such as olive oil, linseed oil, and sesame oil, varied significantly based on source plant, regional conditions, and processing methods. This inconsistency made standardization difficult, unlike mineral oils, which could be more uni-

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formly refined and tested for transformer applications [1].

5. Gas absorption and dielectric breakdown

Studies demonstrated that vegetable oils had higher gas absorption rates compared to mineral oils. Dissolved gases such as oxygen and carbon dioxide under electrical stress led to an increased risk of dielectric breakdown, an unacceptable risk in high-voltage equipment [5][6].

6. Early failures and industry perception

Historical operational failures involving vegetable oils cemented negative perceptions regarding their reliability. Meanwhile, incremental improvements in mineral oil refining and handling supported its entrenchment as the preferred insulating medium [3].

7. Technological context of the early 20th century

During the early decades of transformer development, technologies like sealed tank designs, antioxidant additives, and controlled oil treatment were not widely available. The vulnerabilities of vegetable oils were thus exposed more readily, reinforcing the dominance of mineral oil.

Modern perspectives

Technological advancements such as the introduction of sealed transformer systems, the development of more robust antioxidant formulations, and improved moisture management strategies enabled the re-emergence of vegetable-based insulating liquids (natural esters) in the late 20th century as viable and environmentally sustainable alternatives to mineral oil. In response to their distinct chemical and physical characteristics,

specific standards such as ASTM D6871 were established to define the performance requirements for natural ester-insulating liquids.

To achieve a meaningful reduction in the overall carbon footprint and to enhance the operational sustainability of power transformers, the development and implementation of effective recycling and recovery processes for all categories of insulating liquids remains a critical necessity.

Conclusion

The early rejection of vegetable oils as transformer insulating liquids was rooted in their poor oxidation stability, high moisture affinity, poor low-temperature performance, variability, and higher gas absorption tendencies. Combined with the technological limitations of the era, mineral oils provided a safer, more reliable solution. Only recent environmental concerns and technological improvements have allowed vegetable oils to be reconsidered as practical alternatives.

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Marius Grisar holds an MSc in Electro-Analytical Chemistry from the Israel Institute of Technology. He has almost 30 years of intense experience in almost all transformer oil test chains, from planning, sampling, and diagnosis to recommendations and treatments, mainly in Israel but also in other parts of the world. He is responsible for establishing test strategies and procedures and creating acceptance criteria for insulating liquids and materials based on current standardization and field experience. In addition, he trains and educates electrical staff on insulating matrix issues from a chemical point of view. He is an active member of relevant Working Groups of IEC, CIGRE, and a former member of ASTM. He is also the author and co-author of many papers, CIGRE brochures, and presentations at prestigious international conferences on insulation oil tests, focusing on DGA, analytical chemistry of insulating oil, and advantageous maintenance policy for oil and new transformers.