

Mineral Oil, White Oil and Synthetic Dielectric Coolants

How Engineered Fluids' Dielectric Coolants Differ from Petroleum based Dielectric Oils

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Overview

Full immersive cooling with dielectric fluids is the future of thermal management for electric motors, batteries and computers. Today's design engineers need to understand the key characteristics of the different dielectric fluids available for use in these applications, and the advantages and challenges relative to one another. This paper describes the engineered dielectric coolants available from Engineered Fluids, LLC, and how they differ from mineral, and other petroleum products.

Mineral Oils

"Mineral oil" is a term applied to a broad range of distillates primarily from petroleum. Most often, mineral oil is the liquid by-product of refining crude oil to make gasoline and other petroleum products. These types of mineral oil are composed mainly of alkanes and cycloalkanes, and are directly related to petroleum jelly. These mineral oils are commodity products sold by oil refineries without any further processing, qualifications, or quality control. Mineral oils are often referred to by other names, such as "paraffin oil", "pale oil" or "neutral oil". The most common uses of mineral oil are as bases or additives in machinery lubricants.

White Oils

"White Oils" are mineral oils that have undergone a further refining process called "hydrotreating." Hydrotreatment removes some impurities found in refined petroleum products. Because they are refined petroleum products, white oils are a mixture of diverse types of petroleum by-products rather than a single homogenous compound. White oils are predominantly used in the manufacture of cosmetics, sun block, laxatives, hair products, and some "food grade" white oils are used as a carrier media for pharmaceuticals.

Engineered Fluids' Dielectric Coolants

Engineered Fluids' manufactures three product lines of synthetic dielectric heat transfer fluids, each for a specific industry application – general semiconductor, electric motors and batteries, and power transformers. Within each product line there are different formulations to further allow an engineer to specify the exact performance and characteristics they require for an application.

The Engineered Fluids' Dielectric Coolants product range is composed of:

ElectroCool®

Biodegradable, non-toxic dielectric coolants specifically formulated for use in full- immersive, single-phase cooling of electronics. Common applications of ElectroCool are the cooling of semiconductors, CPUs, GPUs, laser diodes, high power magnets, and other electrical systems that require high density heat transfer in either open and closed systems. There are six grades of ElectroCool product available with different viscosities as well as specific formulations for increased fire resistance, and use in sealed systems.

AmpCool®

Biodegradable, non-toxic dielectric coolants with and without lubricants specifically designed for use in full- immersive, single-phase cooling of electric motors, electric motor controllers, and batteries. Common applications of AmpCool is the cooling of batteries and motors in electric vehicles, mobile and stationary energy storage systems. There are five grades of AmpCool product available with different viscosities, increased fire resistance and use in sealed systems. In addition, two of the AmpCool products are specifically formulated with long wearing lubricants for use with electric motors.

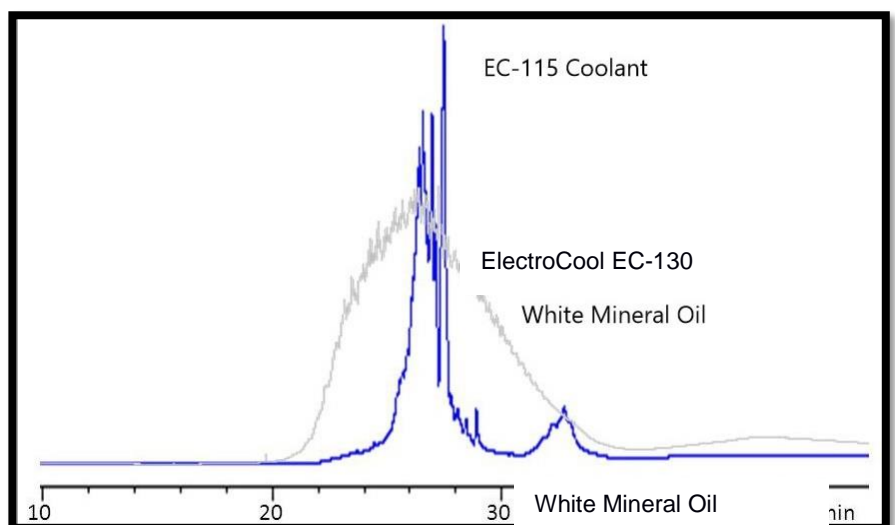
VoltCool®

Biodegradable, non-toxic dielectric coolants specifically designed for use in high power and distribution transformers. There are three grades of AmpCool product available with different viscosities and varying levels of fire resistance.

Purity and Consistency

Engineered Fluids' Dielectric Coolants are manufactured in a proprietary process from highly processed synthetic chemicals, not petroleum oils. ElectroCool is manufactured through a

Figure 1 - Gas Chromatograph display that shows the wide variety of petroleum distillates in a white oil, versus the narrow distribution of synthetic chemicals in ElectroCool EC-130.



controlled process of chemical reactions in precision equipment. As a result, ElectroCool Coolants contain very few impurities, when compared with white and petroleum oils which are derived from the petroleum distillation process. This purity is a key attribute of ElectroCool in comparison with white oils as it eliminates issues such as oxidation resistance and material compatibility.

The gas chromatograph results, pictured Figure 1, demonstrates how a common processed brand of white mineral oil is composed of a very wide spectrum of different hydrocarbons, each with a different boiling point, biodegradation characteristics, dielectric strength, and molecular structure. Engineered Fluids' ElectroCool EC-130, on the other hand, is specifically formulated as a dielectric coolant and is manufactured under strict quality control and tolerances. Therefore, ElectroCool Coolants' key characteristics such as viscosity, flash and fire points, heat transfer characteristics and dielectric strength are all precisely controlled. They are consistent between containers in the same batch and between batches. This consistency is key to enabling the thermal engineer to properly design the cooling solution with precision performance and ensure material compatibility within the system. White oils lack of consistency in composition leaves the thermal engineer and the end-user at high-risk of experiencing an expensive and potentially catastrophic material compatibility issue with each new container. Given that single-phase immersive cooling is typically used in high rack and server densities, and in mission critical applications, any such failures and the associated down-time caused by material compatibility are likely to be of consequential proportions both in terms of work lost as well financial implications.

Health, Safety and Biodegradation

Regardless of any other aspect of a dielectric coolant's performance, the health and safety of the end-users and of the earth's environment should be a significant factor in choosing a dielectric fluid. This is an area of critical difference between Engineered Fluids' Dielectric Coolants and those of white oils and other petroleum products. According to the findings of the National Institute of Health's 14th Report on Carcinogens, published in 2016 concludes that:

"Untreated and mildly treated mineral oils are known to be human carcinogens based on sufficient evidence of carcinogenicity from studies in humans."^{1,2}

The net effect being that white oils are known carcinogens according to the US National Institute for Health, and the International Agency for Research on Cancer³, regulated as a hazardous substance by OSHA in the United States (particularly for oil mists formed in response to heating or aeration)⁴, and considered a hazardous substance by the US Environmental Protection Agency

1 <https://ntp.niehs.nih.gov/ntp/roc/content/profiles/mineraloils.pdf>

2 <https://www.cancer.org/cancer/cancer-causes/general-info/known-and-probable-human-carcinogens.html>

3 <http://monographs.iarc.fr/ENG/Monographs/suppl7/>

4 https://www.osha.gov/dts/chemicalsampling/data/CH_258700.html

requiring the same hazardous materials handling requirements as other petroleum oils⁵, and is not considered biodegradable per standard CEC L33b laboratory testing.

Biodegradation of hydrocarbons is affected by several factors: molecular weight, molecular structure and the presence of impurities that act as bacterial toxins. As noted above, refined petroleum oils have a wide distribution of molecular weights. The higher molecular weight fractions are extremely difficult for bacteria to break down and use as a source of carbon, which slows the process of biodegradation. In addition, petroleum oils are a mixture of many types of molecular structures: linear carbon chains, highly branched chains, circular aromatic structures and crystalline waxes. This variety of molecular structures is present in crude oil, and they are not separated during the refining process. As a result, the refined base oil or white oil can require years to be completely biodegraded.⁶

The third factor influencing biodegradation rate is the presence or absence of impurities that act as biotoxins. Again, crude oil contains many types of chemical compounds. Some are organic hydrocarbons (pyridines, quinolines, carbazoles, amides, ketones, aldehydes, peroxides, and furans) and some are inorganic (sulfur compounds, metals, salts and chemical soaps). A few of these impurities are removed or changed during the refining process, but many are carried through unchanged and are present in the refined product. These impurities are what give petroleum its characteristic smell. The impurities act as toxins to bacteria that are present in soil and water, and slow the biodegradation rate of petroleum oils.

Conversely, Engineered Fluids' Dielectric Coolants are synthetic engineered fluids which are manufactured in chemical reactions under tightly controlled conditions. The Engineered Fluid's Dielectric Coolants are virtually a single molecular species, which can be broken down easily by bacteria in soil or water. They do not contain the impurities seen in petroleum oils, which accounts for their exceptional clarity and lack of odor. There are no biotoxins to impede the process of biodegradation. In comparison, using the CEC L33b laboratory methodology over the standard 28-day term, the Engineered Fluid's Dielectric Coolants are more than 94% biodegraded versus white oil of 80 SUS viscosity are only 35-40% biodegraded.⁷

The absence of impurities also accounts for the excellent health and safety profile of Engineered Fluids' Dielectric Coolants. In white and other petroleum oils it is the quantity and variety of impurities – ketones, aldehydes, peroxides, metals and sulfur compounds, that give petroleum its unpleasant smell and can cause allergic skin and respiratory reactions. The ultra-pure

⁵ <http://www.libertyenviro.com/regulatory-alert-epas-spcc-rules-commonly-overlooked/>

⁶ Factors Affecting the Rate of Biodegradation of Polyaromatic Hydrocarbons, Sihag et al, International Journal of Pure and Applied Bioscience (2014)

⁷ Af. Journal of Biotechnology Vol. 8 (6), pp. 915-920, 20 March, 2009

biodegradable, non-toxic dielectric coolant from Engineered Fluids are far safer for the environment and the health of workers. Engineered Fluid's Dielectric Coolants are anti-allergenic, non-reactive, and have no smell, ensuring that users who work with the coolants regularly are not subject to the skin rashes, respiratory issues, and nausea often associated with direct and prolonged contact with petroleum products. In addition, Engineered Fluids Dielectric Coolants have a very low vapor pressure across their entire working temperature range; they do not vaporize into the surrounding air when used in open systems at high temperatures. As such, Engineered Fluids Dielectric Coolants will not condense on clothing, hair, skin, or the surrounding equipment.

Fit for Purpose and Known Characteristics

Given that refiners of white oils do not manufacture or specify their products as dielectric coolants it is understandable why they do not provide or guarantee any of the basic characteristics required by the thermal engineer to properly design an electronics cooling solution. Key characteristics such as heat transfer characteristics, dielectric strength and moisture content are neither tested nor guaranteed by refiners of these compounds.

White oils are commodity product and their intended applications do not require high precision, other than the most basic characteristics of viscosity, specific gravity, and flash point. A detailed reading of supplier's white oil datasheets finds that even these basic characteristics are described as "typical characteristics" and often include the disclaimer that they are "subject to change without notice." Unfortunately for the thermal engineer intending to immerse and cool expensive, high precision electronics this presents an important quandary. Since white oils are not subject to strict quality standards in regard to composition, thermodynamic characteristics, dielectric strength and moisture content this leaves the thermal engineer having no real knowledge or assurance of these products' single drum base composition nor their batch-to-batch homogeneity. Unfortunately, short of testing and qualifying every single drum of petroleum or white oil to ensure it is within the design tolerance for their cooling solution, there is no way for the thermal engineer or manufacturer to have any such assurance. Even white oils from the same refiner are not guaranteed as homogenous in terms of composition, heat transfer characteristics, dielectric strength and moisture content.

This lack of fit for purpose and quality therefore places all the responsibility on the thermal and product engineers to somehow ensure the performance of their cooling solution as well as the safety of their end-users, not to mention the financial investments incurred in development, manufacturing and operations.

Engineered Fluids' ElectroCool Dielectric Coolants, on the other hand, are the product of a controlled and precision manufacturing process design specifically to ensure that the critical

characteristics of every product are precisely known, tested and guaranteed. Every production batch of ElectroCool is carefully tested and is not released to inventory unless it passes all manufacturing quality specifications. Contrary to commodity petroleum oils, ElectroCool Dielectric Coolants are standardized, tested and guaranteed.

Table 1, below, provides a comparison of what characteristics are provided and guaranteed by manufacturers of white oil vs. Engineered Fluids' ElectroCool Coolants.

Table 1 - Comparison of key Characteristics provided by manufacturers

Characteristics Tested, Provided, and Guaranteed.	Engineered Fluids' ElectroCool® Coolants	Mineral and White Oils
Viscosity	<i>Guaranteed</i>	<i>Provided</i>
Density	<i>Guaranteed</i>	<i>Provided</i>
Flash Point	<i>Guaranteed</i>	<i>Provided</i>
Color	<i>Guaranteed</i>	<i>Provided</i>
Fire Point	<i>Guaranteed</i>	<i>Not Tested</i>
Refractive Index	<i>Guaranteed</i>	<i>Not Tested</i>
Dielectric Strength	<i>Guaranteed</i>	<i>Not Tested</i>
Moisture Content	<i>Guaranteed</i>	<i>Not Tested</i>
Specific Heat	<i>Guaranteed</i>	<i>Not Tested</i>
Thermal Conductivity	<i>Guaranteed</i>	<i>Not Tested</i>
Coefficient of Thermal Expansion	<i>Guaranteed</i>	<i>Not Tested</i>
Materials Compatibility	<i>Guaranteed</i>	<i>Not Tested</i>

Formulation and Processing

As noted earlier, white oils and petroleum base stocks are not formulated by refiners for use as dielectric coolants. Refiners do not process these products for their dielectric or heat transfer characteristics. This impacts a number of elements regarding how refiners actually blend and process white oils. Probably the most important aspect from a thermal design perspective is that white oils contain impurities that are in fact hydrophilic. This absorption of water from the surrounding air can have a dramatic impact on the dielectric strength of white oils. Depending on the manufacturing process and how the white oils are stored the dielectric strength can diminish rapidly over time. This is especially the case in hot and humid environments.

In addition, white oils and petroleum base oils are not treated to prevent oxidation due to ageing.

As such, mineral oils and white oils begin to oxidize immediately when they contact air. The heat of the electronics further accelerates this oxidation reaction⁸. The first byproducts of hydrocarbon oxidation are peroxides and ketones, which then turn into acids. These acids cause the oil to darken and then thicken, which has a deleterious effect on the optical clarity and heat transfer efficiency of the oil. Even more harmful is that these acids then attack copper and zinc in the circuitry that is being cooled.

Conversely, all Engineering Fluids' Dielectric Coolants are manufactured at Engineered Fluids' processing facility. Engineered Fluids' proprietary formulations makes these coolants extremely resistant to oxidation and water absorption. The manufacturing of Engineered Fluids' Dielectric Coolants occurs at high temperatures and under high vacuum, such that upon packaging, the average moisture content of Engineering Fluids Dielectric Coolants is less than 10 ppm and the dielectric breakdown strength is above 60 kV (ASTM D1816). In addition, because they are filtered at the sub-micron level to remove any particulate contaminants. The result is a dielectric coolant specifically made for heat transfer in electrical equipment.

Viscosity and Temperature Stability

Viscosity and temperature stability are key aspects of a coolant that can be leveraged by thermal engineers to optimize their solution and thereby decrease circulating flow rates in order to reduce power consumption and fluid transport infrastructure. Having precise knowledge of both the minimum flow temperature as well as the highest operating temperature, combined with a precise graph of associated viscosity allows the thermal engineer to specify the proper coolant based on the operating temperature and targeted heat transfer required.

Unlike petroleum and white oils, Engineered Fluids' Dielectric Coolants do not contain any wax, which gives them far superior low temperature pour points. This is critical when using the Coolants in electric vehicles and batteries which must operate in temperatures below 0C. In addition, this allows Engineered Fluids' products to be stored in outdoor uninsulated enclosures without fear of material breakdown due to low temperatures. Table 2, below, compares the pour points and viscosity ranges of Engineered Fluids' EC-120 Dielectric Coolant, compared with those of a commodity 80 SUS petroleum oil and white oil.

Table 2 - Comparison of Viscosity and Pour Points

	Engineered Fluids' ElectroCool®	80 SUS Mineral Oil¹⁰	White Oil¹¹
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⁸ The Tribology Handbook, M. Neal, 1973, Reed Elsevier, pub.

¹⁰ Calpar™ Product datasheet, Calumet Specialty Products

¹¹ Penreco Corporation, Drakeol 9™ White Mineral Oil Specifications

	Coolants EC-120⁹		
Kinematic Viscosity @ 40 C	3.8	12.5-14.0	13.2-17.0
Kinematic Viscosity @ 100 C	1.39	3.1-3.4	Not Reported
Pour Point °F / °C	-58/-50	1/-17	0/-18

Table 2 demonstrates several important things:

- The absolute difference in viscosity (and therefore heat transfer effectiveness) between Engineered Fluids' Dielectric Coolant and petroleum oils. Engineered Fluids Dielectric Coolants are far lower in viscosity, and therefore require far less pumping power and have much higher heat transfer efficiencies than petroleum products
- The wide range of permissible viscosities of petroleum products. This critical characteristic is not tightly controlled by the refiners of petroleum oils as they are for Engineered Fluid's Dielectric Coolants. One batch of mineral or white oil can have significantly different characteristics than another batch, even from the same refiner.
- The extreme difference in pour points between an Engineered Dielectric Coolant and a petroleum oil. Any outdoor application or storage of a petroleum product will encounter significant issues with oil flow at low temperatures.

Material Compatibility

From our experience in assisting thermal engineers design single-phase, immersive cooling solutions for electronics, we find that their area of greatest concern is regarding material compatibility. This is understandable given the primary application of dielectric coolants is the submergence of very expensive equipment with the expectation that will operate with no downtime and over extended periods lasting years. Engineered Fluids has invested a lot of its research and development efforts in solving the material compatibility issues that are experienced with white oils.

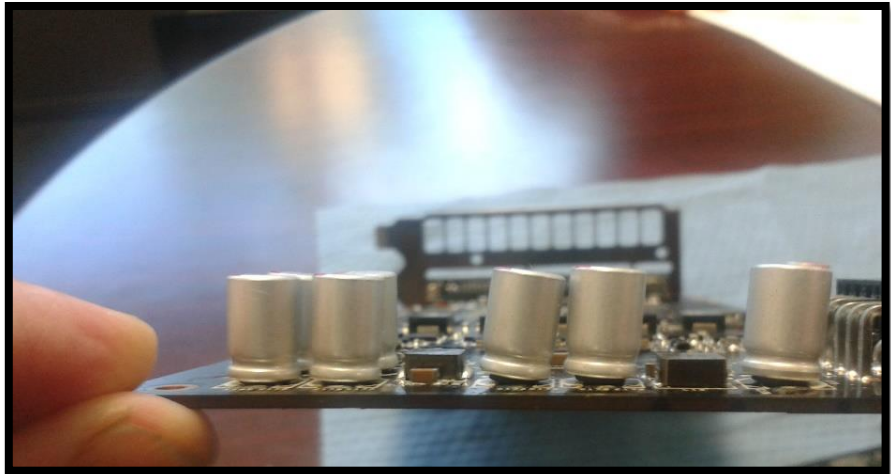
Again, because white oils are not intended to be fit for purpose as dielectric coolants, the refiners who produce it make no guarantees regarding what materials their white oils will interact with and how. Rubber and plastic, including wire insulation and semiconductors like capacitors with gaskets, are often trouble spots for system designers. These compounds stiffen or swell in the presence of white oils, causing these components to short out due to loss of insulation or even become entirely detached from the circuit board due to swelling. Another more problematic area

⁹ ElectroCool® Product datasheet, Engineered Fluids, LLC.

is the delamination of multi-layer circuit boards. As covered earlier the presence of acids in the white oils due to oxidation, combined with the interaction of other impurities, can affect the bonding mechanisms in multi-layer boards. These types of delamination can cause catastrophic failures in power supplies and other complex high and medium voltage circuitry in electronic devices.

Each product in Engineered Fluids' range of Dielectric Coolants is specifically formulated to ensure material compatibility with common materials used in its target industrial application. In addition,

Figure 2 - This picture shows capacitor failure on a GPU board that was cooled by immersion in white oil. The oil was absorbed into the rubber seats under each capacitor causing a swelling effect due to material incompatibility thus causing the capacitors to "pop" off the boards.



Engineered Fluids' is the only manufacturer in the industry to offer a Material Compatibility warranty based on accelerated failure testing. In addition, Engineered Fluids is always willing to work directly with manufactures of servers, batteries, and other electronic systems to ensure that Engineered Fluids' products will not cause unwanted interactions with common materials. Engineered Fluids also maintains a growing list of certified, recommended, and not recommend materials which are compatible with each coolant.

Engineered Fluids' ElectroCool Dielectric Coolants are highly resistant to oxidation and ageing. Laboratory testing shows that ElectroCool coolants have a sealed system have a service life exceeding 20 years, many times more than that of raw white oils.

Heat Transfer Effectiveness

The heat transfer efficiency of a cooling fluid depends on many physical parameters; however none is more important that viscosity. With white oil, the thermal engineer is restricted to those viscosities available from refiners, unfortunately given their intended purpose higher viscosities is the norm for white oils. While higher viscosity can be good in terms of additional flammability resistance, it can also dramatically diminish the heat transfer capabilities of a fluid, while also increasing the power required to circulate the coolant effectively. It is critical to choose a Dielectric Coolant that has the right balance of characteristics to ensure the correct level of cooling

effectiveness with the high fire resistance at the least cost of operation. Each of Engineered Fluids coolant product lines offer the thermal engineer a broad range of options, each specifically designed to find this balance.

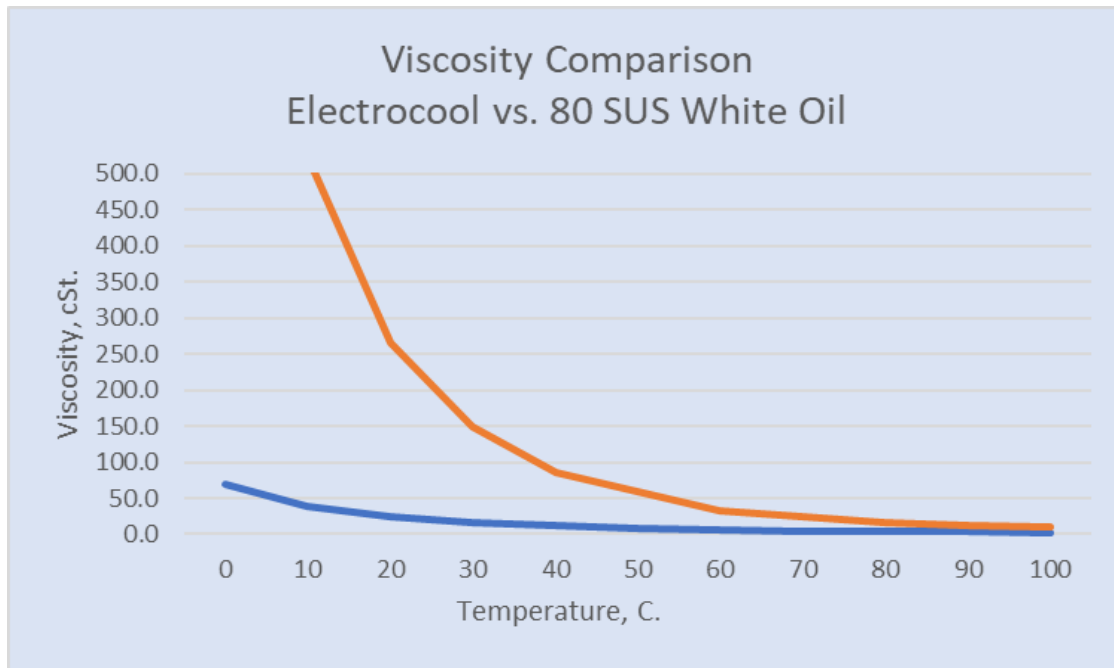


Figure 3 - Comparison of Viscosity over temperature

Figure 4, above, illustrates the difference in viscosity between 80 SUS White Oils (such as Finavestan A80B) and ElectroCool EC-130 Coolant. At typical server operating temperatures, the difference in viscosity, and the difference in heat transfer effectiveness, is significant.

Summary

This paper has examined many points of differentiation between petroleum and other white oils and Engineered Fluids' Dielectric Cooling Fluids.

Petroleum base oils and white oils are commodity petroleum products, made for use as lubricants, cosmetics, and other applications. Engineered Fluids' Dielectric Coolants have been developed and manufactured specifically as dielectric coolants and are intended to be used cool computer servers, batteries, electric motors, and other high and medium power electronic circuitry.

Petroleum and white oils contain a wide variety of chemicals that were present in the original crude oil, and were not removed by the refining process. These chemicals include calcium, magnesium and iron salts, many different sulfur compounds, aldehydes, ketones, peroxides and furans. These impurities not only have deleterious effects on the electrical characteristics of the petroleum, but

also hinder biodegradation and cause unwanted allergic skin and respiratory reactions in workers who handle or breath the oil vapors.

White and petroleum oils are sold with minimal specifications, and have wide variation in key characteristics, such as volatility, moisture content, dielectric strength and viscosity, between refiners and even between batches by the same refiner. Engineered Fluids' products are made to exact specifications in controlled conditions and whose characteristics are tested and guaranteed to the buyer. There are no variations between batches with Engineered Fluids' coolants, and certificates of analysis are available with each batch manufactured.

When choosing a dielectric coolant, a thermal engineer must consider not just the cost of the coolant itself, but the overall total ownership cost of the entire system as well as its reliability. Engineered Fluids' lines of Dielectric Coolants have been formulated specifically for this purpose and exhibit none of the draw backs and health hazards of petroleum based oils.

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