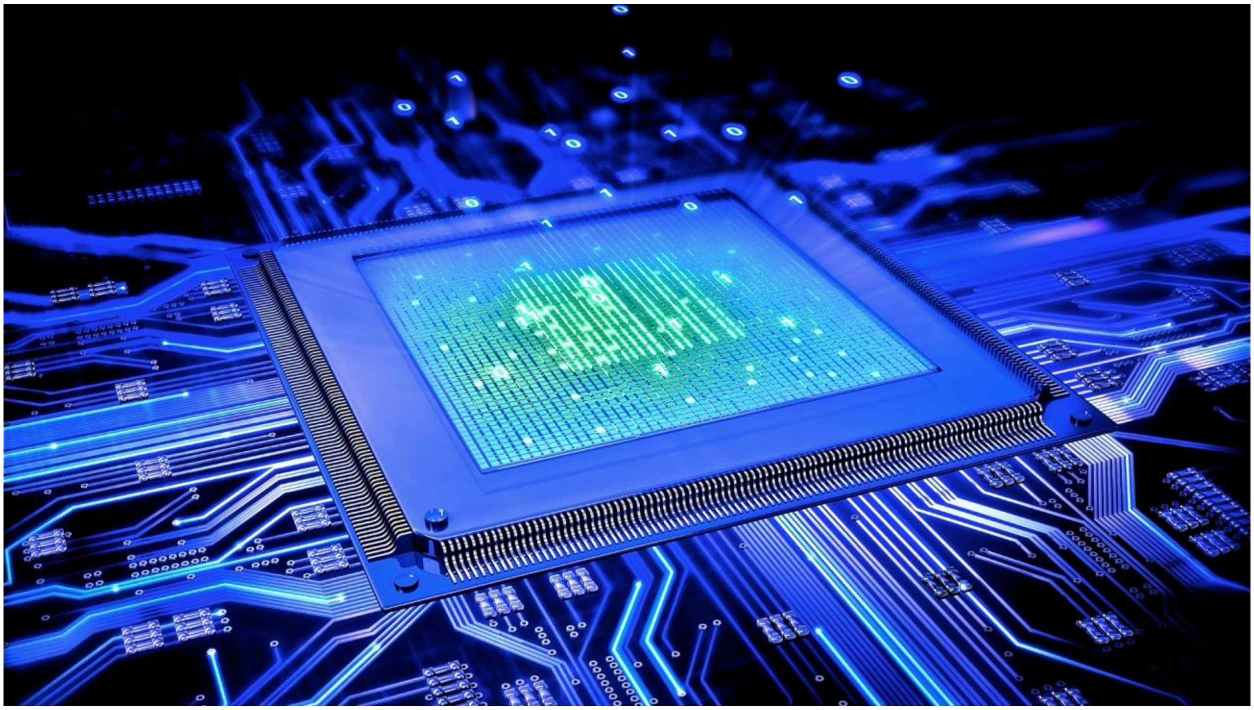

Choosing the Right Fluid for Electronics Cooling:

Seven Dimensions of a Decision:

An Aid for Thermal Engineers

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Executive Summary:

Advances in package density and power capacity of electronic circuits are driving research in more efficient cooling solutions. Direct contact liquid cooling is the least expensive, simplest and most easily scalable way to cool electronics, from individual circuit boards to server installations. The proper choice of the heat transfer fluid can optimize cooling performance and the service life of the electronics being cooled.

There are five different dielectric cooling fluids most often considered for electronics applications:

- Petroleum oil – mineral transformer or light neutral oil.
- White oil – pharmaceutical or technical grade hydrogenated mineral oil
- Fluorinated oil – specialized heat transfer fluids with fluorine substitution
- Vegetable oil – purified soy or other vegetable oil
- Synthetic isoparaffin – synthetic neutral oils made with gas-to-liquid process

This study identified the seven most important parameters of heat transfer fluids in electronics applications:

- Heat Transfer Effectiveness
- Electrical Insulating Properties
- Oxidation Stability
- Material Compatibility
- Worker Health and Safety
- Biodegradation and Environmental Fate
- Cost

Each of the fluids was evaluated and compared on each decision parameter. At the end of the comparison, isoparaffin fluids represent the best combination of efficiency, stability, safety and cost. These oils are efficient at heat transfer, they're food grade, biodegradable, and are resistant to oxidation.

For more information or a summary of this study, please contact tech@dsiventures.com

Introduction

Advances in package density and power capacity of electronic circuits are driving research in more efficient cooling solutions. New heat transfer fluids and cooling system design are needed to cool the next generation of circuits effectively and inexpensively. This paper outlines the seven most important characteristics of liquid phase cooling systems and assists design engineers in properly evaluating heat transfer fluid options.

Studies have identified direct contact, liquid phase cooling as the most efficient and least expensive means of cooling electronics assemblies (1, 2) Direct contact liquid cooling systems are the simplest and least expensive to build and operate. They're not pressurized and don't need specialized pumps.

Seven Key Characteristics to Consider

There are seven important characteristics to consider when evaluating a heat transfer fluid. They are:

- Heat Transfer Effectiveness
- Electrical Insulating Properties
- Oxidation Stability
- Material Compatibility
- Worker Health and Safety
- Biodegradation and Environmental Fate
- Cost

Let's look at each of these fluids in light of the seven parameters:

Heat Transfer Effectiveness

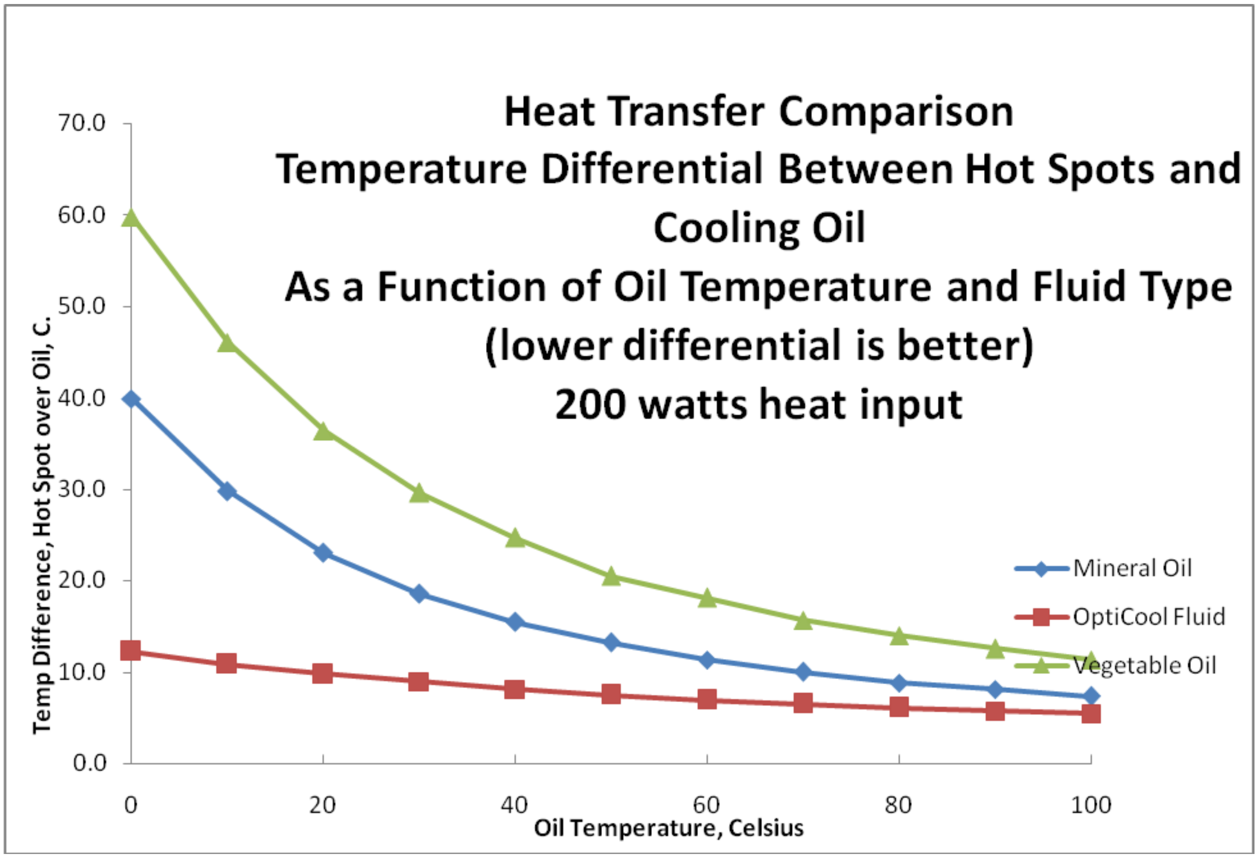
Heat transfer efficiency is obviously one of the most important characteristics of a dielectric cooling fluid. Heat transfer in a given application is a function of the physical characteristics of the cooling medium and the design of the cooling system. Many physical characteristics of the fluid change with temperature and fluid flow patterns. For example, whether the fluid flow is laminar or turbulent depends on viscosity (itself a function of temperature), the shape of fluid flow channels and the profile (the "smoothness") of the walls of the flow channels.

Prior studies (7,8,9) have investigated the relationship between different fluid characteristics (viscosity and density) in several different fluids and the effect that these characteristics have on cooling performance. As would be expected, among similar chemistries of fluids, dynamic viscosity exerts the largest effect on the heat transfer performance. Models have been developed that engineers to change the application parameters and immediately see the predicted effect on cooling performance. They also allow a comparison of the relative performance of different fluids in a given system. Iterative analysis allows design engineers to change the fluid path architecture and flow patterns so that heat transfer is optimized.

The graph below details the difference in heat transfer capabilities of the three fluids in a closed system where the oil passes through ducting, over a heat source, removing the heat for later release to the atmosphere. This particular model uses a 200 watt heat-generating component, 2x2 inches in size. This graph demonstrates heat transfer effectiveness by calculating the difference in temperature between a hot component, such as a CPU, and the bulk of the heat transfer fluid, after the entire system has come to a thermal equilibrium. A lower differential value indicates that as the fluid passes over the hot spot, it picks up enough energy that its temperature almost reaches that of the hot spot itself. A less efficient fluid will not pick up as much heat in the system, and the differential temperature will be greater.

Note that at all temperatures, the isoparaffin fluid maintains the lowest differential between the hot spot temperature and the fluid's temperature. This is due to the influence of its lower viscosity, in comparison with the other fluids.

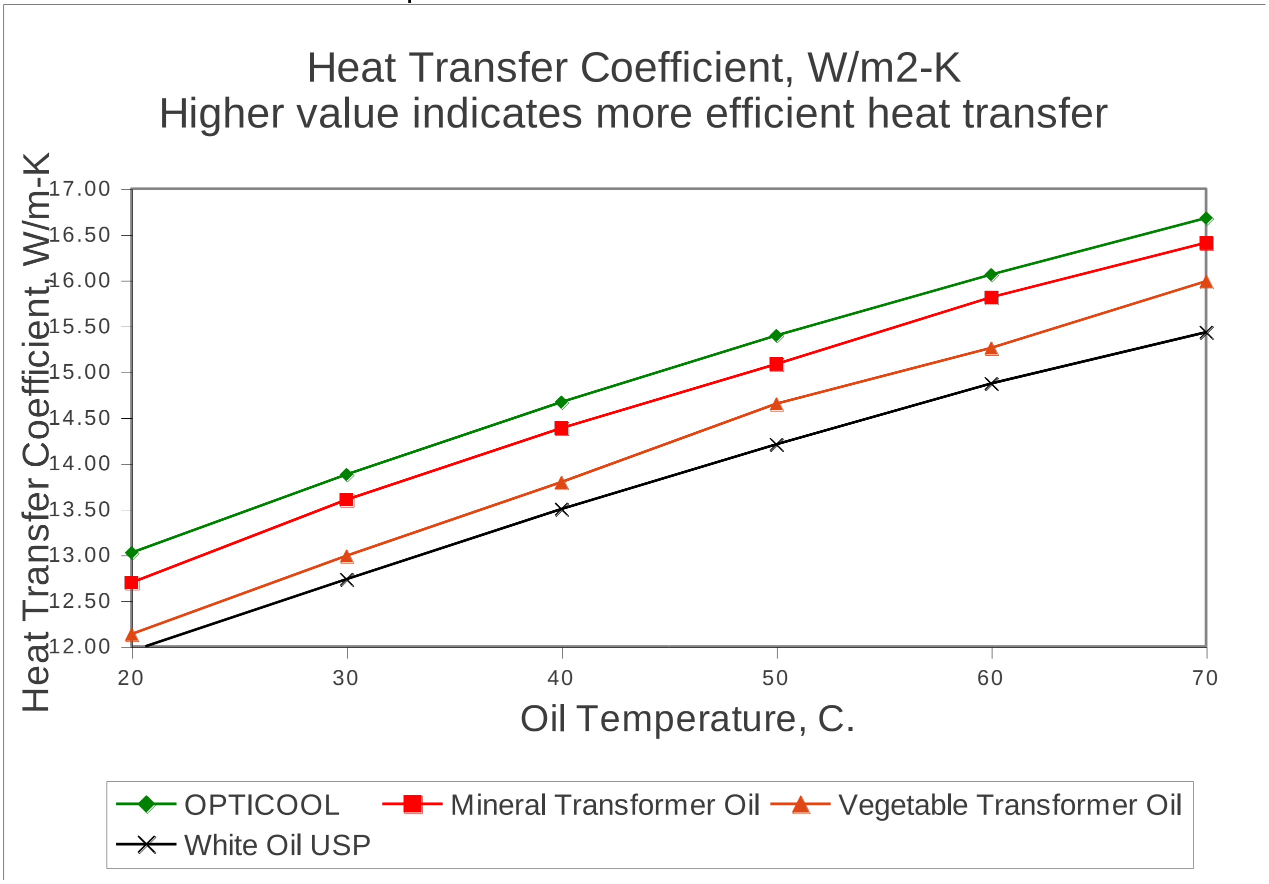
Figure One



The difference between the cooling performance of isoparaffin (labeled OptiCool Fluid in this example) and the other oils is more pronounced at lower temperatures. Note also the relatively stable viscosity of the isoparaffin fluid as temperatures range from 0 to 100 degrees Celsius.

In this particular equipment design, when the oil temperature is 80 degrees C., the benefit of cooling with isoparaffin fluid is approximately 8 degrees C. when compared with using a vegetable-based insulating oil. That is, the hot component temperature will be approximately 8 degrees lower when the cooling oil is isoparaffin type. Other equipment designs show similar results.

Figure Two
Comparison of Heat Transfer Coefficients



A newer cooling prediction model has been developed that allows engineers to change dimensions and heat input of the heated surface area, and compare the heat transfer coefficients of different fluids. We can see the same pattern of heat transfer ranking between the different fluids, again driven by the viscosity. Between similar chemistries of heat transfer fluids in liquid phase contact cooling, the fluid with the lowest viscosity will be the most efficient.

An example is shown where the model is given a fluid approach velocity of 2 m/s, and a heated plate, 20 x 30 cm at 90 ^{o}C . Figure 2 compares the heat transfer coefficients of several fluids in contact with this heat source. The lower viscosity of the isoparaffin (OptiCool) fluid drives the heat transfer effectiveness.

Figure Three

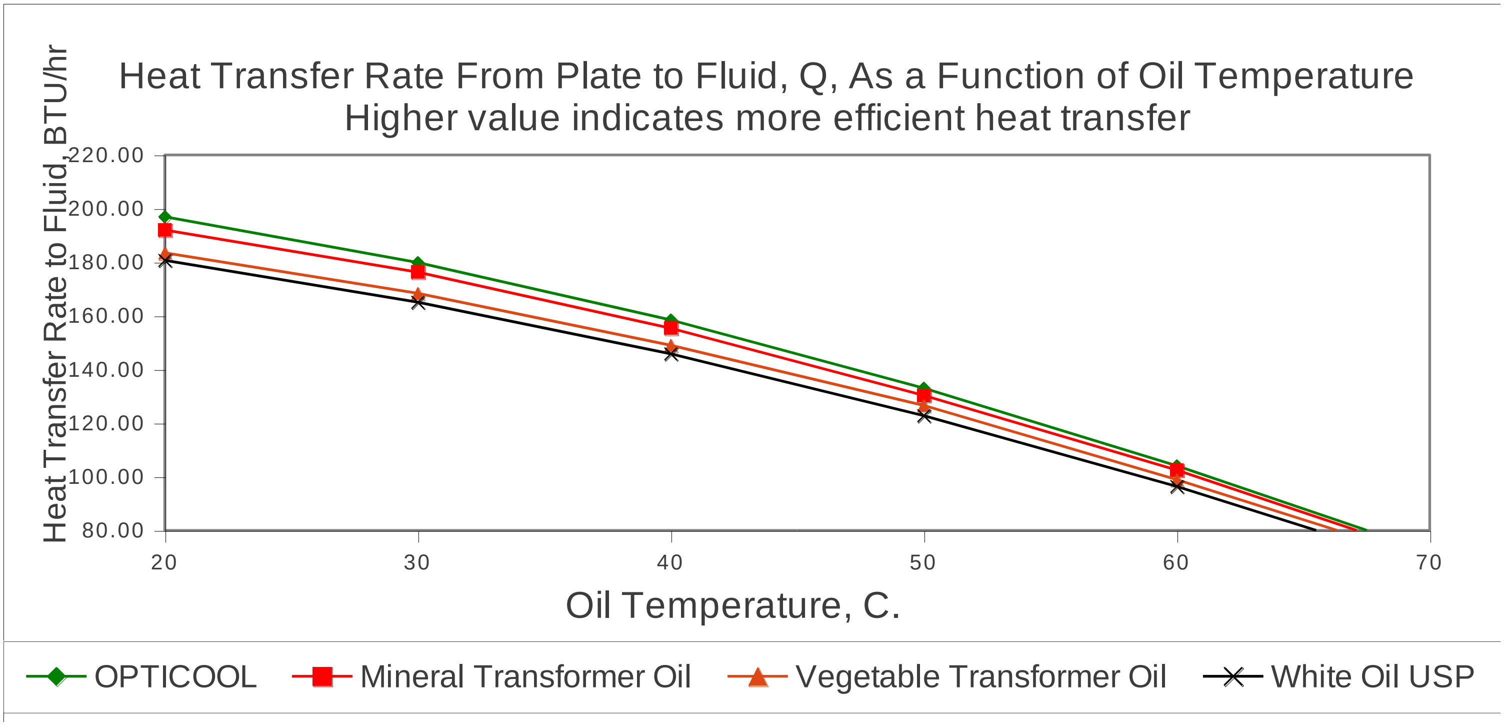


Figure Three shows Q, the rate of heat transfer from the plate to the liquid, given in BTU/hour, as the fluid temperature approaches the temperature of the plate. As before, differences are more pronounced with higher fluid viscosity at lower temperatures.

A more in-depth analysis of heat transfer characteristics of various fluids is given in the references (9).

Electrical Characteristics:

The electrical characteristics of each of these oils is acceptable, and none are remarkably better or worse than the others. Each type of fluid is inherently non-polar, and thereby a good electrical insulator. Each fluid can be readily dried with heat and vacuum. Each fluid has a very high dielectric strength, above 50,000 volts at an electrode gap distance of 0.08"

Table One
Dielectric Strength of Dielectric Cooling Fluids

	Mineral Oil	White Oil	Vegetable Oil	isoparaffin
Dielectric Strength, ASTM D1816, KV (0.08" gap)	>50	>50	>50	>50

Oxidation Stability:

Hydrocarbon oils oxidize when exposed to heat and oxygen, but some oils will resist oxidation longer than others, and thereby have a longer service. Buildup of acids and sludge auto-catalyzes the oxidation process, and can can shorten the life of equipment. Polymerized sludge and varnishes coat heat transfer surfaces, rapidly diminishing the effectiveness of the cooling system.

Fluorinated fluids have exceptional oxidation stability, and are not tested in the referenced report.

Mineral oils generally have good resistance to oxidation. Their useful life can be enhanced with the right additives. Most petroleum based dielectric oils have aminic or phenolic oxidation inhibitors added to increase the oil's useful life.

White oils generally have poor oxidation stability. Their manufacturing process includes hydrogenation, which removes naturally occurring antioxidants. New antioxidants are not usually added to white oils, because the oils are often as ingredients in pharmaceutical or food grade products. White oils are not recommended in heat transfer applications unless additional antioxidants have been added.

In comparison with other fluids, vegetable oils have remarkably poor resistance to oxidation. The oxidation reaction in vegetable oils is different than that which occurs in petroleum oils. In vegetable oils, when the oil breaks down, it polymerizes, or gels. Because of this phenomenon, vegetable-based oils should be used only in closed systems where contact with air can be prevented. They are not recommended for use in systems with a high heat flux density or where hot spot temperatures exceed 100 C.

Photo One

Vegetable Oil Dielectric Fluid
Polymerized After 36 hrs @ 90 C
with Bubbled Air

Isoparaffin oils generally have very good oxidation stability because of the characteristics of their synthetic base oil. Synthetic isoparaffins age more slowly than conventional petroleum based oil. This is partially due to the range of chemicals found in petroleum oil and the lack of impurities in synthetic base oils. Heat transfer fluids using isoparaffin oils contain added antioxidants to lengthen the service life of the product.

Table Two, below, shows the results of a laboratory test for oxidation resistance. This test bubbles oxygen through a test tube of oil, held at 100 ^{o}C. The test monitors the buildup of acids and sludge - both byproducts of oxidation - in the oils. Ideally, an oil should not create either.

The vegetable oil polymerized, turning into a gel, within the first 72 hours. White oils that have oxidation inhibitor added respond in the same manner as mineral oils, with acids and sludge buildup as the heat breaks the oil down, driving the oxidation reaction. Isoparaffin oils exhibit the highest stability against oxidation and aging.

Table Two

Modified ASTM D2440 oxidation test (bubbling O_2, 100 ^oC., Cu wire catalyst)

	Isoparaffin Fluid	Mineral Oil	White Oil	Vegetable Oil
72 Hours				
Sludge, wt %	0.01	0.06	0.04	Polymerized
Acid Value mg KOH/g	0.01	0.10	0.09	Polymerized
164 Hours				
Sludge, wt %	0.01	0.11	0.17	Polymerized
Acid Value Mg KOH/g	0.01	0.44	0.49	Polymerized

Compatibility with Equipment Construction Materials:

Beyond being an effective cooling medium, an electronics cooling fluid must not affect the physical characteristics of the other components of the cooling system. The proper dielectric cooling fluid for the application will be compatible with all circuit board and other materials that the fluid will contact. As few fluids were specifically developed for use with computer components, long term compatibility has to be carefully considered. Fluids can affect components in a variety of ways; by causing rubber or plastic components to swell and soften, by causing some components to harden and crack, or by delamination of circuit boards.

One of the ways that fluids are tested for potential incompatibilities is to determine the fluid's solubility toward rubbers and similar compounds. A common test measures the lowest temperature at which aniline will dissolve in the oil. Aniline is a chemical that has a molecular structure that is similar to a variety of rubber compounds. A low value of aniline point indicates that the oil is a more aggressive solvent, which is closely linked to rubber and plastic swelling and softening, circuit board delamination and other long term compatibility problems.

Table Three
Aniline Points of Heat Transfer Fluids

	Mineral Oil	White Oil USP	Vegetable Oil	Iso-Paraffin
Aniline Point, ASTM D611, C.	74	94	60	92

Being paraffinic in nature, the white oil and isoparaffin have the highest aniline points, and therefore the least solvency toward materials. The vegetable oil is an ester, which exhibits high solvency.

There are more direct ways to measure compatibility of materials and propensity to delaminate or destabilize circuit board material, increasing entropy of the system.

Accelerated aging studies can indicate potential problems in material compatibility. Standard Test Method ASTM D3455 ("Standard Test Methods for Compatibility of Construction Material with Electrical Insulating Oil of Petroleum Origin") can be modified to apply to a wider range of materials, beyond petroleum oils. The modified method ages materials in an oven at 150 C., for 14 days, then evaluates the samples for changes appropriate to that material. Elastomers are tested for weight change, composite materials are tested for tensile strength and evidence of delamination, etc. Further information on material compatibility testing in dielectric fluids can be found in the references (9).

Photo Two shows a circuit board aged in a vegetable-based dielectric fluid. Solvent attack and the beginning of delamination can be seen (marked by arrows in this photograph).

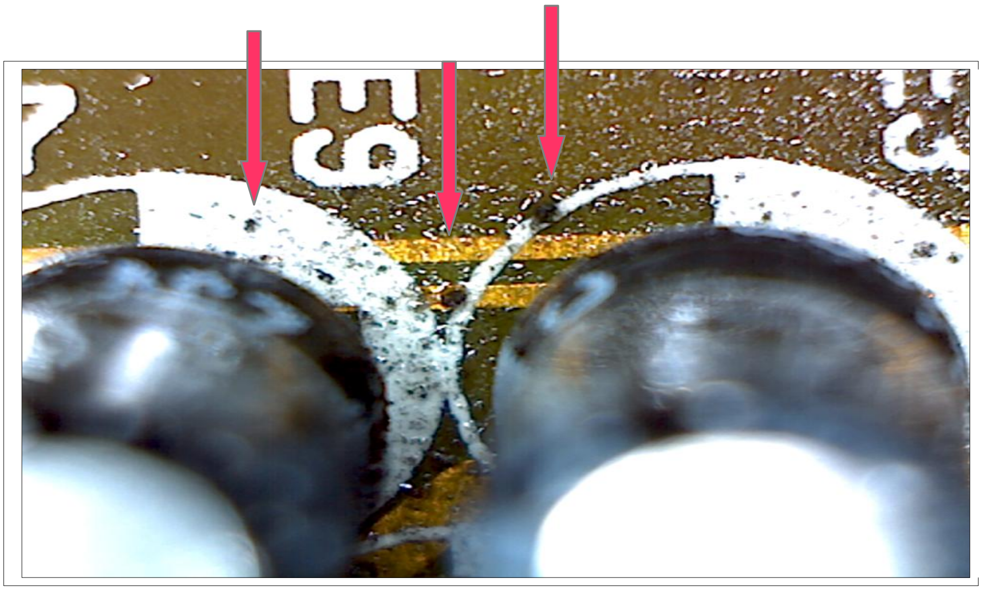


Photo Two, Circuit Board Aged in Natural Ester (Vegetable Oil)

Photo Three shows the same circuit board in a less aggressive fluid, synthetic hydrocarbon. Note the absence of pits and areas of dissolved circuit substrate.

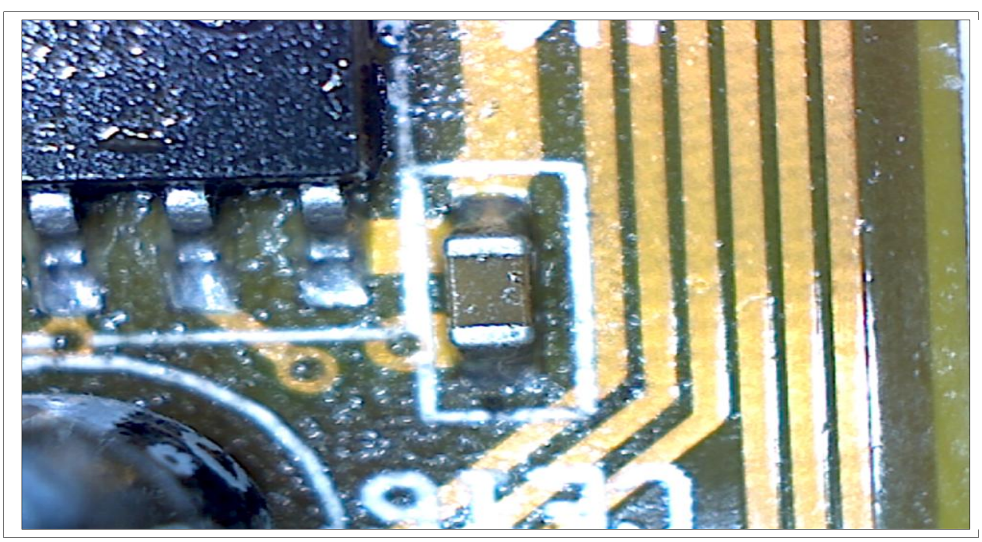


Photo Three, Circuit Board Aged in isoparaffin

Of the oils tested, the white oil and isoparaffin oils have the least solvency power and will be less aggressive to paints, varnishes, rubbers, and other materials than fluids that contain vegetable oils or conventional mineral oil.

Fluids chosen should be compatible with gasket and sealing materials that are commonly used in electronics applications. Some of these materials are:

Nitrile Rubber
Buna-n Rubber
Cork
Silicone Rubber
Viton
Fluorocarbon Rubber

For more on the subject of fluid molecular structure and its effects on material compatibility, please see referenced work. (8)

Environmental Fate and Worker Health:

Heat transfer fluids must be evaluated in terms of their effects on the health of workers who are exposed to the fluids, as well as to the environment. Worker exposure can be via inhalation of gas or aerosol, via ingestion or by skin exposure. Environmental fate should consider toxicity to marine and soil organisms as well as biodegradation rate and completeness.

Worker Exposure, Health and Safety

All of the fluids evaluated in this study have acceptable worker exposure limits. Inhalation risk at operating temperatures is very low with each. Skin contact with these fluids is treated by washing with soap and water. All four fluids are considered non-toxic and non-hazardous. For specific information on each fluid, please refer to the Material Safety Data Sheet available from the respective manufacturer.

Biodegradation

Biodegradation refers to the ability of microbes in soil and water to use the oil as a source of carbon. Biodegradation breaks the oil molecules down slowly. Due to the structure of the different oil molecules, some oils biodegrade more rapidly and completely than others. Biodegradation rates are dependent upon temperature, the type of soil (thick clay is different from sandy loam), water (salt water is different from fresh water), and many other factors.

Laboratory tests are used to compare the biodegradation rates of different fluids. In one of the common tests, an oil sample is mixed with water and bacteria, then held for 28 days at a fixed temperature. The concentration of oil in the water is measured before and after the test, showing how much was degraded by bacteria during the test period.

Table 4
Typical Biodegradation Data for Various Fluids:

	Mineral Oil	White Oil	Vegetable Oil	Isoparaffin
Biodegradation, 28 Day Method CECL33a, %	15-35	25-45	>90	>90

Flammability

Flammability of the fluid must be considered when evaluating overall health and safety characteristics. As the voltages encountered in electronics cooling applications are usually low, the chance of an electrical arc being present as an ignition source are very small. Mineral transformer oil has been used in distribution transformers located indoors for over 70 years (5) For these reasons, the flammability characteristics of standard mineral transformer oil (fire point > 145 C) is considered to be an acceptable minimum yardstick for heat transfer fluid in electronics cooling application.

With this in mind, a comparison of fire points for the different fluids under consideration is shown below:

Table 5
Flammability Characteristics for Various Fluids:

	Fluorinated Fluids	Mineral Oil	White Oil	Vegetable Oil	Isoparaffin
Fire Point, ASTM D92, degrees C.	non flammable	145 min	150-200	>300	160

All of the candidate fluids meet the minimum standards set for flammability for electrical insulating fluids.

Cost

While not the primary consideration when choosing a heat transfer medium, the cost of the fluid must be taken into account. When calculating oil use, be sure to consider spills, waste, leakage and waste, which together can equal several percent of overall use.

Fluid costs per gallon range from $8.00 - 10.00 for mineral oil and white oil, $13 - 15 for vegetable oils, $18 - 20 for synthetic hydrocarbons to more than $200 /gallon for fluorinated fluids.

Overall Comparison

Choosing the right heat transfer fluid for electronics cooling requires a multi faceted evaluation of fluid candidates. The chart below shows the different parameters:

Parameter	Fluorinated Fluids	Mineral Oil	White Oil	Vegetable Oil	isoparaffin
Heat Transfer Effectiveness	Very Good	Good	Good	Good	Very Good
Electrical Characteristics	Good	Good	Good	Good	Good
Material Compatibility	Very Good	Good	Very good	Fair	Very Good
Oxidation Stability	Very Good	Good	Fair	Poor	Very Good
Worker Safety and Health	Good	Fair	Very Good	Very Good	Very Good
Biodegradation	Poor	Poor	Poor	Very Good	Very Good
Cost	$$$$	$	$	$$	$$

Conclusion:

This study has examined the various types of heat transfer fluids available to the electronics thermal engineer. The fluids were compared along parameters of heat transfer, oxidation resistance, material compatibility, worker health and safety, environmental safety and cost. The comparison shows that isoparaffin fluids are efficient, safe, and cost effective solutions to ever-increasing demands in electronics cooling.

OptiCool Fluid:

OptiCool Fluid® is an isoparaffin based dielectric heat transfer fluid manufactured by DSI Ventures, Inc. OptiCool has been used for over 10 years to cool electrical circuitry in transformers, RF and microwave transmission devices and computer systems.

OptiCool Fluid is a colorless, odorless, food grade isoparaffin oil. With a very low viscosity and high thermal conductivity, OptiCool Fluid has extremely high heat transfer coefficients, making it ideal for removing heat from circuitry with high heat flux densities.

Contact DSI to find out more about OptiCool Fluid and its electronics cooling applications.

sales@dsiventures.com
Tel: 903-526-7577

References:

1. http://gizmodo.com/5940551/intel-is-cooling-entire-servers-by-submerging-them-in-oil

2. Redacted.

3. http://www.electricenergyonline.com/?page=show_article&article=230

4. ANSI/IEEE Standard C57.12 "Standard Guide for Loading Mineral Oil Insulated transformers"

5. "Insulating Materials for Design and Engineering Practice"; F.M. Clark

6. Redacted.

7. ASTM Standard Specification D3487 “Standard Specification for Electrical Insulating Oil of Mineral Origin”, American Society for Testing and Materials

8. Redacted.

9. Biodegradation of mineral oils – A review

10. Emmanuel O. Aluyor and Mudiakeoghene Ori-jesu. African Journal of Biotechnology Vol. 8 (6), pp. 915-920, 20 March, 2009

11: Biodegradation data from http://www.substech.com/dokuwiki/doku.php?id=biodegradation_of_oils and supplier testing.