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Environmentally Acceptable Transformer Fluids: An Update

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Electric Power Research Institute (EPRI)

This is an EPRI Technical Update report. A Technical Update report is intended as an informal report of continuing research, a meeting, or a topical study. It is not a final EPRI technical report.

NOTE

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PRODUCT DESCRIPTION

This report offers information about the physical, dielectric, chemical, and environmental properties of transformer fluids and their operational impacts. Companies can use this information to choose environmentally acceptable "green" fluids.

Results and Findings

Graphs compare mineral oil with environmentally acceptable transformer fluids such as high-temperature hydrocarbons, silicones, synthetic esters, and natural esters. The reader can easily see which fluids have, for example, the highest fire point or the best biodegradability. Virgin and in-service fluids, impacts on utility operations, and cost considerations are discussed.

U.S. Environmental Protection Agency (EPA) reports on natural ester fluids verify manufacturer data on general performance and biodegradation, showing that these fluids meet and exceed industry standards. No significant issues are associated with the long-term use of these fluids in utility transformers. However, regulatory spill cleanup standards lag in acknowledging the reduced risk from natural ester fluids.

Challenges and Objectives

Company personnel responsible for purchasing, installing, operating, maintaining, and ensuring the environmental compliance of fluid-filled transformers can use this report as a handbook of environmentally acceptable fluids. First cost of these fluids is still higher than that for conventional mineral oil, but is decreasing. Life-cycle costs of environmentally acceptable fluids are likely to be less than those for conventional mineral oil. An EPA regulatory decision to ease spill cleanup requirements for natural ester fluids would make a significant contribution to life-cycle cost saving.

Applications, Values, and Use

There is widespread use of environmentally acceptable fluids in distribution transformers, with increasing applications in substation transformers. According to manufacturers, environmentally acceptable fluids are being used in more than 200,000 transformers in the United States.

Information in this report will help companies choose environmentally acceptable transformer fluids that meet specifications for individual fluid properties, as well as overall specifications for general use. By outlining the impacts of transformer fluids on utility operations, the report supports a life-cycle cost perspective. It also supports environmental stewardship by highlighting desirable features of alternative "green" fluids.

EPRI Perspective

As energy companies look for ways to make their operations more environmentally friendly, they are frequently choosing to use vegetable-based, natural ester fluids in distribution transformers. As more companies consider this option, there is a need for data on companies' operating experiences with these biodegradable fluids. There is also some indication that these fluids will be less expensive and have less environmental impact. In response to this need, EPRI conducted an analysis of environmentally acceptable transformer fluids. This analysis updates a previous EPRI report, *Environmentally Acceptable Transformer Fluids: Phase 1 State-of-the-Art, Phase II Laboratory Testing of Fluids* (1000438), published in 2000.

Approach

This report considers four different types of environmentally acceptable transformer fluids: high-temperature hydrocarbons, silicones, synthetic esters, and natural esters. It compares the performance of these fluids with that of mineral oil on an array of physical, dielectric, chemical, and environmental properties. Data for the comparisons come from recent product literature for all fluids, Environmental Technology Verifications and current specifications for virgin and in-service natural ester fluids, and an informal survey of member companies' experiences using natural ester fluids. The report discusses how fluids impact utility operations and reviews cost considerations.

Keywords

Transformer fluid
"Green" fluid
Environmentally acceptable
Natural ester
Synthetic ester
Silicone
High-temperature hydrocarbon
Mineral oil
Distribution transformer

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1 INTRODUCTION

In 2000, an *IEEE Industry Applications Magazine* article stated that "It is increasingly important that dielectric fluids provide a better balance of functional performance inside the transformer versus environmental impact in the event of release" (McShane 2000). In the same year, the Electric Power Research Institute (EPRI) published its report, *Environmentally Acceptable Transformer Fluids: Phase 1 State-of-the-Art, Phase II Laboratory Testing of Fluids* (EPRI 2000). In the ensuing decade, a new class of environmentally acceptable fluids based on vegetable oils has become widely available and the electric utility industry has accumulated significant experience with these new "natural ester" fluids. At the same time, traditional mineral oil has continued to compete with other environmentally acceptable transformer fluids, such as those based on high-temperature hydrocarbon, silicone, and synthetic esters.

The push for environmentally acceptable transformer fluids has several drivers, including:

- *Environmental Stewardship*—Electric utility companies recognize the need to minimize the environmental impact of transformer fluid spills. Fluids that are biodegradable and nontoxic to aquatic life are highly desirable. Responding to a 2009 survey conducted by EPRI (EPRI 2009), one company using a natural ester fluid in some transformers said, "Our primary driver is that it's a 'greener' alternative."
- *Carbon Footprint*—Fabricating transformer fluids from materials other than petroleum reduces carbon emissions to the environment. Cooper Power Systems (CPS) calculates that a $1 million purchase of its soy-based Envirotemp® FR3™ transformer fluid is equivalent to removing 13 cars from the road. In its Building for Environmental and Economic Sustainability (BEES) evaluation, the National Institute of Standards and Technology judged Envirotemp FR3 to be essentially carbon neutral throughout its life cycle.
- *Renewable Resources*—The production of vegetable-based transformer fluids relies on renewable resources, such as soybeans or sunflower seeds, and sustainable farming and manufacturing practices supporting the domestic economy. It should be easy to recycle and reuse these materials. The choice of non-petroleum-based fluids alleviates concerns about the present supply and future availability of petroleum oil.
- *Risk Management*—Environmentally acceptable transformer fluids have higher flash and fire points than mineral oil. Use of these fluids improves fire safety—an important issue for a fleet of aging transformers subject to increased risk of explosion and fire that can cause heavy collateral damage. Likewise, use of these fluids in transformers located near ecologically sensitive areas, such as wetlands, may reduce environmental risks related to potential spills.
- *Asset Life Extension*—CPS claims that retrofilling a mineral oil-filled transformer with Envirotemp FR3 natural ester fluid can double the remaining transformer life by slowing insulation aging. Again, this is an important benefit for companies with fleets of middle-aged transformers because it could allow them to defer capital costs without compromising safety.
- *Market Forces*—Demand for environmentally acceptable transformer fluids in distribution and power transformers continues to rise in response to the environmental impact of

conventional mineral oil. As of 2009, more than 150,000 distribution class transformers filled with natural ester fluids were in service and demand is growing for power class transformers (> 35 kVA, > 10 MVA) filled with these fluids.

The purpose of this report is to help readers choose available, effective, and affordable transformer fluids that are environmentally acceptable. To accomplish this, the report draws on information from recent product literature for all fluids, Environmental Technology Verifications and current specifications for virgin and in-service natural ester fluids, and an informal survey of member companies' experience using natural ester fluids.

The report considers four different types of environmentally acceptable transformer fluids—high-temperature hydrocarbons, silicones, synthetic esters, and natural esters. It compares the performance of these fluids with that of mineral oil on an array of physical, dielectric, chemical, and environmental properties. Finally, it discusses the operational impacts of performance on each property and reviews cost considerations.

2
TRANSFORMER FLUID TYPES

Functions of Transformer Fluid

Transformers alter the voltage of electricity generated at power plants before it reaches customers or other end users. Fluids that fill thousands of in-service transformers ensure their safe and reliable operation for this purpose.

Transformer fluids electrically insulate and cool transformer components. To appreciate these functions, it is helpful to review the design of a typical transformer. A transformer is a fluid-filled metal tank housing a core with windings. The windings are separate coils of paper-insulated wire wrapped around a steel laminate core. Without submersion in fluid, energized transformer components would short on contact with the metal tank and they would overheat.

Transformer fluids with dielectric properties make excellent insulators because they do not conduct electric current. They are said to exhibit dielectric strength and are called dielectric fluids. The most commonly used transformer, or dielectric, fluid is mineral oil. Acting as insulators, dielectric fluids prevent transformer damage by controlling electrical shorts, fires or explosions, and gas formation.

Dielectric fluids cool transformer components by conducting heat away from them. The windings, core, and connected circuits of an in-service transformer generate heat with increasing load. The heated fluid surrounding them expands, flows up the winding ducts to the top of the metal case, and flows back down cooling pipes—dissipating its heat to the outside air by radiation and convection. This cycle of heat exchange occurs by natural convection in smaller transformers, or with assistance from pumps, fans, or cooling water in larger transformers. Acting as a coolant, dielectric fluid prolongs transformer life by preventing overheating that causes the paper insulation on the windings to deteriorate. In its role as a coolant, dielectric fluid must remain stable at high temperatures over an extended period of time.

Transformer tank tops are sealed (sometimes with a nitrogen gas cap) to prevent fluid in the tank from oxidizing on contact with air. Oxidation introduces impurities and degrades fluid performance.

Fluids discussed in this report are those suitable for use in distribution class and small power class transformers. For purposes of setting test limits for virgin mineral insulating oil, the *IEEE Guide for Acceptance and Maintenance of Insulating Oil in Equipment* (IEEE C57.106 2006) places transformers in the following voltage classes:

- Distribution transformers < 36 kV
- Power transformers 36–69 kV
69–230 kV
230–345 kV
> 345 kV

Fluids designed for use in larger industrial transformers, traction (high-speed rail) transformers, pipe-type cables, or specialty electrical equipment lie outside the scope of this report.

Types of Transformer Fluid

When transformers were first introduced in the 1890s, manufacturers filled them with mineral oil—a fluid exhibiting favorable dielectric strength and performance characteristics. Since then, mineral oil has been in continuous use as a transformer fluid.

However, mineral oil is rated as flammable by Underwriters Laboratories (UL®). Responding to the need for a truly nonflammable fluid that could be used in transformers installed where fire was a particular hazard, manufacturers introduced polychlorinated biphenyl (PCB) fluids in the 1930s. Unfortunately, PCB fluids (called Askarels®) exhibited very unfavorable environmental characteristics. Classified by the U.S. Environmental Protection Agency (EPA) as persistent, bioaccumulative toxins, they were banned from U.S. production in 1976.

Aside from mineral oil, most dielectric fluids in contemporary use are rated as less flammable by UL. Previous EPRI reports (EPRI 2000, EPRI 1998) characterized some of these fluids, describing their performance in power company electrical equipment and their environmental properties. The present report updates previous information, focusing on environmentally acceptable transformer fluids that are less flammable. It places special emphasis on the most recently developed, vegetable-based fluids.

As shown in Table 2-1, less flammable hydrocarbon-based fluids include highly refined high-temperature hydrocarbons and synthetic esters. Less flammable silicone-based fluids are fabricated using polydimethylsiloxane (PDMS), a manmade organic polymer known for its flow properties. Less flammable vegetable-based fluids are refined from beans or seeds.

In addition to flammable, petroleum-based VOLTESSO 35 mineral oil, Table 2-1 lists five brand name transformer fluids representing the broad types described above. They are Beta Fluid® high-temperature hydrocarbon, XIAMETER® PMX-561 silicone, MIDEL® 7131 synthetic ester, Envirotemp® FR3™ natural ester, and BIOTEMP® natural ester fluids. These are the fluids characterized in the present report.

Table 2-1
Flammable and Less Flammable Transformer Fluids

Fluid Type	Base	Brand Name	Source
UL Flammable			
Mineral Oil	Naphthenic Petroleum	VOLTESSO 35	Imperial Oil Limited
UL Less Flammable			
High-Temperature Hydrocarbon	Paraffinic Petroleum	Beta Fluid®	DSI Ventures, Inc.
Silicone	Polydimethylsiloxane (PDMS)	XIAMETER® PMX-561	Dow Corning Corporation
Synthetic Ester	Polyol Ester Hydrocarbon (Pentaerythritol)	MIDEL® 7131	M&I Materials Ltd
Natural Ester	Vegetable	Envirotemp® FR3™	Cooper Power Systems
		BIOTEMP®	ABB, Inc.

Mineral Oil

VOLTESSO 35, manufactured by Imperial Oil Limited (Imperial Oil), is a highly refined mineral oil based on naphthenic petroleum. Naphthenic mineral oil contains cycloalkanes (organic hydrocarbons with carbon atom rings) that make VOLTESSO 35 flammable, but fluid at low temperatures. The manufacturer offers VOLTESSO 35 as a Type I dielectric fluid with normal oxidation resistance conferred by adding less than 1% oxidation inhibitor. VOLTESSO 35 has a long history of use in North America and provides a reference point for comparison with other transformer fluids.

More than 750 million liters of mineral oil are used in fluid-filled transformers in the United States each year. Mineral oil is often chosen for outdoor transformer installations where flammability presents fewer hazards and low first cost is the most important consideration. VOLTESSO 35 has performed very well in transformers for service periods of more than 20 years.

High-Temperature Hydrocarbon Fluid

Beta Fluid is a high-temperature hydrocarbon fluid offered by DSI Ventures Inc. Natural high-temperature hydrocarbon fluids are highly refined mineral oils derived from paraffinic petroleum, which has a higher molecular weight than naphthenic petroleum. Beta Fluid derives its fire-resistant properties from *n*-alkanes (organic hydrocarbons with a linear, or “normal,” arrangement of carbon atoms). However, its higher molecular weight makes it less fluid at lower temperatures.

DSI Ventures Inc. introduced Beta Fluid in 1994. Since then, thousands of transformers filled with Beta Fluid have been placed in service.

Synthetic high-temperature hydrocarbon fluids are polyalphaolefins (PAOs) created by polymerizing olefins (alkanes). PAOs have defined molecular weight, purity, and stability.

Because they are costly and tailored for specific applications, these specialty fluids are not discussed in this report.

Silicone Fluid

Silicone fluids are complex molecules (polymerized siloxanes) based on silicon rather than carbon. Dow Corning Corporation (Dow Corning) uses a silicon-based organic polymer called polymethylsiloxane (PDMS) to manufacture its silicone fluid, XIAMETER PMX-561. (XIAMETER PMX-561 is a new name for Dow Corning's 561 Silicone Transformer Liquid of the same formulation.) PDMS gives XIAMETER PMX-561 unusual flow properties. For example, although it is highly viscous at room temperature, XIAMETER PMX-561 flows much more freely than mineral oil at low temperatures. It is also less flammable and self-extinguishing when the source of a fire is removed.

Companies began using silicone fluids in transformers in the 1970s, particularly to replace nonflammable but toxic PCB fluids. For years, they have chosen silicone fluids such as XIAMETER PMX-561 for both indoor and outdoor applications requiring Factory Mutual (FM)-approved less flammable transformer fluids. In one example, museum officials installed indoor transformers filled with Dow Corning 561 Silicone Transformer Liquid to ensure critical fire safety at the Los Angeles Getty Center museum.

Synthetic Ester Fluid

MIDEL 7131 is a synthetic ester fluid manufactured by M&I Materials Ltd. Synthetic esters are organic compounds chemically synthesized from fatty acids and alcohol. In the case of MIDEL 7131, a synthetic "polyol" ester is created by combining fatty acids with a polyhydric alcohol (penthaerythritol). Synthetic ester fluids offer less flammability and easy pouring at very low temperatures.

MIDEL 7131 is a member of the family of esters traditionally chosen to lubricate jet engines. For more than 30 years, European manufacturers such as Siemens have used MIDEL 7131 in their distribution, power, traction (railroad), and industrial transformers. More than 1000 distribution class transformers filled with MIDEL 7131 were in service worldwide in 2000.

Synthetic ester fluids are best suited to applications where a high fire point, high lubricity, and very low pour point justify their higher cost. For example, MIDEL 7131 was first used in the United States in 1984 in compact railroad rolling stock transformers with forced fluid flow to remote heat exchangers and very high duty requirements.

Natural Ester Fluids

Natural esters found in vegetables such as soybeans and sunflower seeds are organic compounds composed of fatty acids and alcohol. These natural esters are called triglycerides because they combine three fatty acids with an alcohol (glycerol).

Processing converts raw vegetable triglycerides into transformer fluids. First, beans or seeds are refined, bleached, and deodorized to create purified, edible vegetable oil. Further processing removes contaminants from the oil and introduces additives to combat oxidation and microbial activity. The results are vegetable-based transformer fluids that share some properties of synthetic ester fluids, such as less flammability, favorable dielectric properties, and biodegradability. But these fluids also share some properties of high-temperature hydrocarbon fluids, such as unfavorably high pour points. Compared with synthetic ester fluids, natural ester fluids cost much less.

Envirotemp FR3

CPS has developed a soybean-based natural ester fluid marketed as Envirotemp FR3. In tests conducted by EPA as part of its Environmental Technology Verification of Envirotemp FR3 (EPA-CalEPA/DTSC 2002a), composition of virgin fluid samples agreed with the manufacturer's formulation:

- monosaturated fatty acids = 23.8% ± 0.1%
- polyunsaturated fatty acids = 59.9% ± 0.1%
- saturated fatty acids = 15.7% ± 0.1%
- antioxidant concentration = 2,787 ppm ± 834 ppm

BIOTEMP

A second popular natural ester fluid is BIOTEMP, developed from sunflower or canola seeds and marketed by ABB, Inc. (ABB). In tests conducted by EPA as part of its Environmental Technology Verification of BIOTEMP (EPA-CalEPA/DTSC 2002b), composition of virgin fluid samples agreed with the manufacturer's formulation:

- oleic acid = 80.1% ± 0.3%
- di-unsaturated fatty acids = 10.5% ± 0.1%
- tri-unsaturated fatty acids = 0.3% ± 0.0%
- saturated fatty acids = 9.2% ± 0.2%
- antioxidant concentration = 3,207 ppm ± 103 ppm

Present Use

Research to develop natural ester fluids began in the early 1990s. By 2009, an estimated 200,000 distribution class and 150 power class transformers filled or retrofilled with natural ester fluids were operating in the United States. Envirotemp FR3 circulated in more than 60,000 of these transformers owned by electric utilities and municipal and rural electric cooperatives.

In an informal 2009 survey, EPRI found that six of seven electric utilities located on the East Coast or in the Midwest were using distribution transformers filled with natural ester fluids. Two companies installed Envirotemp FR3-filled transformers, while one company installed transformers filled with either Envirotemp FR3 or BIOTEMP. The rest of the companies responded to the survey by discussing their use of natural ester fluids without specifying brand.

Companies said they were installing transformers filled with natural ester fluids on pole and pad mounts, and in underground network vaults. One company switched from mineral oil to Envirotemp FR3 for transformers in underground vaults because the natural ester fluid can "run hot" with less risk of ignition, due to its superior fire resistance. This company issued a blanket order for the purchase of Envirotemp FR3-filled transformers after damages sustained during Hurricane Ike in 2008. Some damaged transformers were located in ecologically sensitive areas, such as near waterways, where fluid biodegradability would be advantageous in the event of a future spill. A second company was using its inventory of 130 transformers filled with natural ester fluids to replace silicone-filled transformers at indoor locations. Originally, the company had chosen fire-resistant silicone over mineral oil for indoor applications, but decided that natural ester fluids would do a better job. To date, none of these companies has reported failure of transformers using the alternate fluids.

Although most utilities purchasing natural ester fluids have approved them for use in distribution transformers, some are investigating their use in large, high-voltage power transformers. These studies are being conducted in cooperation with the fluid manufacturers and the results remain proprietary. One company is serving as a beta tester for the use of Envirotemp FR3 in substation transformers.

Retrofills and Blends

Owners may wish to retrofill transformers with fluids other than those supplied by the original equipment manufacturer. Retrofilllng can upgrade old transformers, increasing their safety and longevity. For example, an indoor transformer filled with mineral oil will pose less fire hazard when retrofilled with a natural ester fluid that has a higher fire point. Most retrofill applications replace mineral oil with another transformer fluid.

For a retrofill strategy to work, the original and retrofill fluids must be compatible. According to product literature, the following fluids are compatible with VOLTESSO 35 mineral oil:

- Beta Fluid high-temperature hydrocarbon
- MIDEL 7131 synthetic ester
- Envirotemp FR3 natural ester
- BIOTEMP natural ester

In theory, ABB claims that BIOTEMP mixes in all proportions with mineral oils, while CPS claims that Envirotemp FR3 is fully miscible with conventional mineral oil. In practice, one company responding to EPRI's 2009 survey said that Envirotemp FR3 and mineral oil did not mix easily, and another company reasoned that it would have to stock both fluids because they are incompatible. Sources agree that XIAMETER PMX-561 silicone fluid is incompatible with mineral oil and the other transformer fluids listed above.

Each fluid manufacturer offers procedural guidance or methods for retrofilling. Manufacturers advise users to follow their guidance and to consult them for answers to specific questions. Typical concerns and procedures to address those concerns are described in U.S. Patent 6613250, "Vegetable Oil Based Dielectric Fluid and Methods of Using Same" (McShane et al. 2003):

> "The dielectric fluids of the invention preferably are introduced into the electrical equipment in a manner that minimizes the exposure of the fluid to atmospheric oxygen, moisture, and other contaminants that could adversely affect their performance. A preferred process includes drying of the tank contents, evacuation and substitution of air with dry nitrogen gas, filling under partial vacuum, and immediate sealing of the tank."

Fluid blends result when the original transformer fluid is incompletely removed, or when a new fluid is used to "make up" or "top off" low levels of a previous fluid. ABB notes that mixing a significant amount of mineral oil with a natural ester fluid would lower the natural ester fluid's flash point appreciably. However, ABB claims that mixing 10% mineral oil with 90% BIOTEMP will not lower the flash point of the blend below the ASTM D6871 minimum limit of 275 ºC (Appendix C).

Annex B of the *IEEE Guide for Acceptance and Maintenance of Natural Ester Fluids in Transformers* (IEEE C57.147 2008) describes key properties of natural ester-mineral oil blends. It is important to determine blend ratios and document blend properties to provide a baseline for future diagnostic tests. However, the *Guide* also states that, "Although in many cases different types of less flammable fluids . . . are miscible, such mixtures should generally be avoided in transformers and fluid processing equipment when possible due to potential negative impact on key environmental or fire safety characteristics."

3
PERFORMANCE BENCHMARKS

The *IEEE Industry Applications Magazine* article mentioned above (McShane 2000) suggested that an environmentally acceptable transformer fluid must, at minimum, be

- nontoxic;
- biodegradable;
- thermally degradable into acceptable, low-risk byproducts;
- recyclable, reconditionable, and readily disposable; and
- not listed as a hazardous material by EPA or the U.S. Occupational Safety and Health Administration (OSHA).

Environmental Technology Verification

In 2002, EPA—in cooperation with the California Environmental Protection Agency (CalEPA), Department of Toxic Substances Control (DTSC)—conducted Environmental Technology Verifications for two natural ester fluids. These Agencies published Environmental Technology Verification reports for Envirotemp FR3 natural ester transformer fluid manufactured by CPS (EPA-CalEPA/DTSC 2002a) and BIOTEMP natural ester transformer fluid manufactured by ABB (EPA-CalEPA/DTSC 2002b). The reports verify performance characteristics of the fluids and accelerate their entrance into the marketplace by informing users and regulators.

Each Environmental Technology Verification included:

- Developing a workplan that CalEPA/DTSC could use to independently evaluate a fluid's performance characteristics.
- Collecting 12 samples from three different virgin product lots and 4 samples from four different in-service transformers (Appendix A, Table A-1).
- Analyzing virgin and in-service product samples for composition and general performance parameters (Appendix A, Table A-2). Fluid samples were sent to Doble Engineering, an independent testing laboratory using ASTM methods (Appendix B).
- Reviewing supporting documents, such as Material Safety Data Sheets (MSDSs), test data gathered by the fluid manufacturer, and historical data gathered by independent testing facilities.
- Comparing test results to the manufacturer's specifications and standard specifications for each fluid property.
- Publishing an Environmental Technology Verification report and certifying the fluid as Environmental Technology Verification tested.

These evaluations are limited to the use of Envirotemp FR3 and BIOTEMP as alternatives to mineral oil or fluids containing PCBs in pole-mounted, small distribution and small power transformers.

Standard Specifications

Table 3-1 lists standard performance specifications for virgin transformer fluids discussed in this report. ASTM D6871, *Standard Specification for Natural (Vegetable Oil) Ester Fluids Used in Electrical Apparatus,* had not been published when EPA-CalEPA/DTSC undertook their 2002 Environmental Technology Verifications of natural ester transformer fluids. In the present report, ASTM D6871 limits are shown for these fluids on performance graphs.

Table 3-1
Standard Specifications for Virgin Fluids

Fluid Type	Specification	Title
Mineral Oil	ASTM D3487-09	*Standard Specification for Mineral Insulating Oil Used in Electrical Apparatus*
High-Temperature Hydrocarbon	ASTM D5222-08	*Standard Specification for High Fire-Point Mineral Electrical Insulating Oils*
Silicone	ASTM D4652-05	*Standard Specification for Silicone Fluid Used for Electrical Insulation*
	IEC 60836 (2005)	*Specifications for Unused Silicone Insulating Liquids for Electrotechnical Purposes* (Silicone Type T-1)
Synthetic Ester	IEC 61099 (1993)	*Specification for Unused Synthetic Organic Esters for Electrical Purposes*
Natural Ester	ASTM D6871-08	*Standard Specification for Natural (Vegetable Oil) Ester Fluids Used in Electrical Apparatus*

ASTM—ASTM International (formerly American Society for Testing and Materials)

IEC—International Electrotechnical Commission

IEEE—Institute of Electrical and Electronics Engineers

Table 3-2 lists standard performance specifications for in-service transformer fluids discussed in this report. IEEE C57.147, *IEEE Guide for Acceptance and Maintenance of Natural Ester Fluids in Transformers*, had not been published when EPA-CalEPA/DTSC undertook their 2002 Environmental Technology Verifications of natural ester transformer fluids. In the present report, IEEE C57.147 limits are shown on performance graphs for these fluids.

Table 3-2
Standard Specifications for In-Service Fluids

Fluid Type	Specification	Title
Mineral Oil	IEC 60422 (2005)	*Mineral Insulating Oils in Electrical Equipment—Supervision and Maintenance Guidance*
	IEEE C57.106-2006	*IEEE Guide for Acceptance and Maintenance of Insulating Oil in Equipment*
High-Temperature Hydrocarbon	IEEE C57.121-1998	*IEEE Guide for Acceptance and Maintenance of Less Flammable Hydrocarbon Fluid in Transformers*
Silicone	IEC 60944 (1988)	*Guide for the Maintenance of Silicone Transformer Liquids*
	IEEE C57.111-1989	*IEEE Guide for Acceptance of Silicone Insulating Fluid and its Maintenance in Transformers*
Synthetic Ester	IEC 61203 (1992)	*Synthetic Organic Esters for Electrical Purposes—Guide for Maintenance of Transformer Esters in Equipment*
Natural Ester	IEEE C57.147-2008	*IEEE Guide for Acceptance and Maintenance of Natural Ester Fluids in Transformers*

IEC—International Electrotechnical Commission

IEEE—Institute of Electrical and Electronics Engineers

4

PHYSICAL PROPERTIES OF TRANSFORMER FLUIDS AND THEIR OPERATIONAL IMPACTS

Sections 4 through 6 compare the performance of four different types of environmentally acceptable transformer fluids—high-temperature hydrocarbons, silicones, synthetic esters, and natural esters—with that of mineral oil for physical, dielectric, and chemical properties. This section compares fluid performance on an array of physical properties including color and visual appearance, flash and fire point, pour point, kinematic viscosity, heat capacity, thermal conductivity, relative density, and coefficient of thermal expansion.

Graphs in each section present comparative performance information for the various transformer fluids. In text, this information is discussed in qualitative terms. Quantitative data used to construct the graphs are available in Appendix A, Table A-2 (Environmental Technology Verification tests of natural ester fluids); Appendix C (standard specifications for natural ester fluids); and Appendix D (values from the product literature for all fluids). Appendix B lists ASTM standard test methods used to obtain the quantitative data.

Each graph comparing virgin fluids includes:

- available values from the product literature for all fluids,
- available values from Environmental Technology Verification tests of natural ester fluids (including manufacturers' limits), and
- available standard specification limits for natural ester fluids.

Additional graphs compare virgin and in-service natural ester fluids. Blank spaces in the graphs indicate that some values were unavailable.

Color and Visual Appearance

Measured Values

The color number of a transformer fluid measures its clarity. A low color number is desirable because it signals clarity that allows visual inspection of transformer components within the tank. Color number is measured using standard test method ASTM D1500. Another standard test method, ASTM D1524, employs visual inspection to gauge the color and cloudiness (turbidity) of a fluid.

Virgin Fluids

According to data from the product literature shown in Figure 4-1, virgin mineral oil, silicone, and natural ester fluids have the same color number. The color number of high-temperature hydrocarbon fluid is three times higher, indicating less clarity.

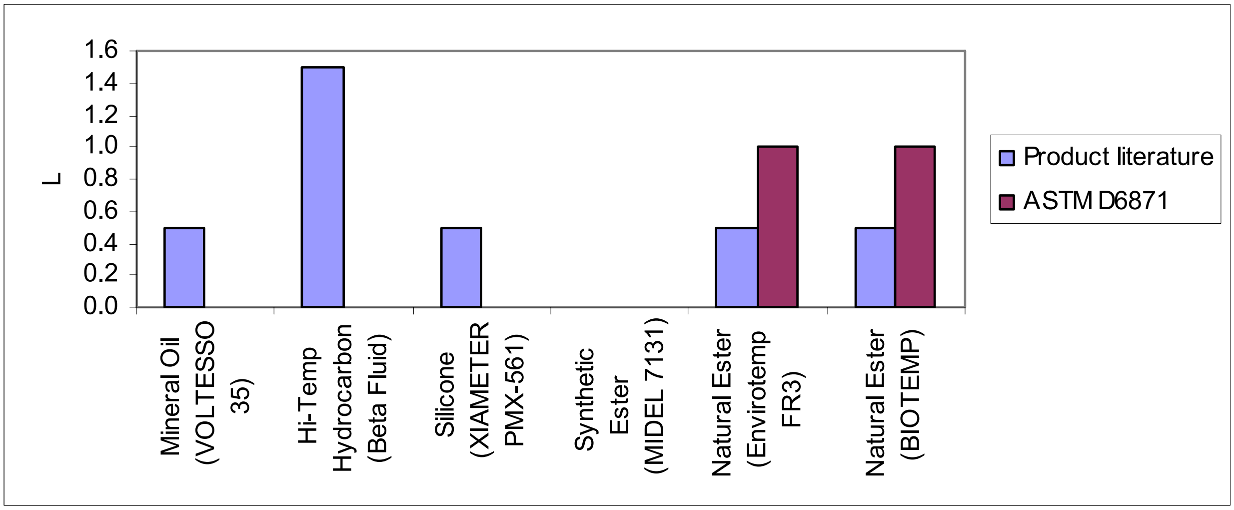


Figure 4-1
Virgin Fluids: Color

ASTM D1500 test results from Appendix D; some values were unavailable

ASTM D6871—*Standard Specification for Natural (Vegetable Oil) Ester Fluids Used in Electrical Apparatus* (Appendix C)

ASTM Color (L)—A single number color scale for grading petroleum products. The scale is defined by 16 glass standards of specified luminous transmittance and chromaticity, graduated in steps of 0.5 from 0.5 for the lightest color to 8.0 for the darkest.

IEEE C57.147 *IEEE Guide for Acceptance and Maintenance of Natural Ester Fluids in Transformers* states that virgin natural ester fluids may be slightly darker and more amber-colored compared with virgin mineral oil. Virgin Envirotemp FR3 has a clear, light green appearance, indicating that the manufacturer has added a color tint for identification purposes. The tint does not influence fluid clarity.

Product literature color numbers for both natural ester fluids fall well below the upper limit specified for virgin fluids by ASTM D6871 *Standard Specification for Natural (Vegetable Oil) Ester Fluids Used in Electrical Apparatus.*

Environmental Technology Verification tests of color and visual appearance were not conducted for virgin natural ester fluids.

In-Service Natural Ester Fluids

Environmental Technology Verification tests of color and visual appearance were not conducted for in-service natural ester fluids.

Operational Impacts

Shipping, Handling, and Storage

Virgin transformer fluids that look dark or cloudy should not be accepted for use. A cloudy fluid may be contaminated by metal particles, insoluble materials, carbon, fibers, or dirt.

Operation and Maintenance

For service-aged transformer fluids, elevated color numbers may reflect deterioration or contamination that can significantly lower the dielectric strength of the fluid. However, adverse changes in dissipation factor and neutralization number may be better indicators of deterioration or contamination. Filtering impacted fluid and identifying contaminants may provide valuable information for correcting problems.

Table 4-1 displays provisional color numbers that should trigger prompt additional investigation of service-aged natural ester fluids, according to IEEE C57.147 *IEEE Guide for Acceptance and Maintenance of Natural Ester Fluids in Transformers.*

Table 4-1
Service-Aged Natural Ester Fluids: Provisional Color Numbers Triggering Prompt Investigation

Transformer Voltage Class	ASTM D1500, L
≤ 69 kV	1.5 minimum
> 69 kV < 230 kV	1.5 minimum
230 kV and above	1.5 minimum

Recovery and Reuse

For service-aged transformer fluids, elevated color numbers may signal the need to remove deterioration products by employing a reclamation process using Fuller's earth.

Flash and Fire Points

Measured Values

According to standard test method ASTM D92, flash point measures the tendency of a transformer fluid to form a flammable mixture with air under controlled laboratory conditions. Fire point measures the tendency of the fluid to support combustion. Higher flash and fire points are advantageous in transformer fluids.

Results of laboratory tests can be used, with other pertinent information, to assess the fire hazard associated with a particular end use of the transformer fluid tested. For example, silicone and synthetic ester fluids typically stop burning when an ignition source is removed. Such "self-extinguishing" fluids present a relatively low fire hazard when used in transformers.

Virgin Fluids

Figure 4-2 shows flash points reported in product literature for virgin VOLTESSO 35 mineral oil and five alternate virgin transformer fluids. Figure 4-3 shows fire points for these fluids. It is clear that mineral oil has lower flash and fire points than the other fluids tested.

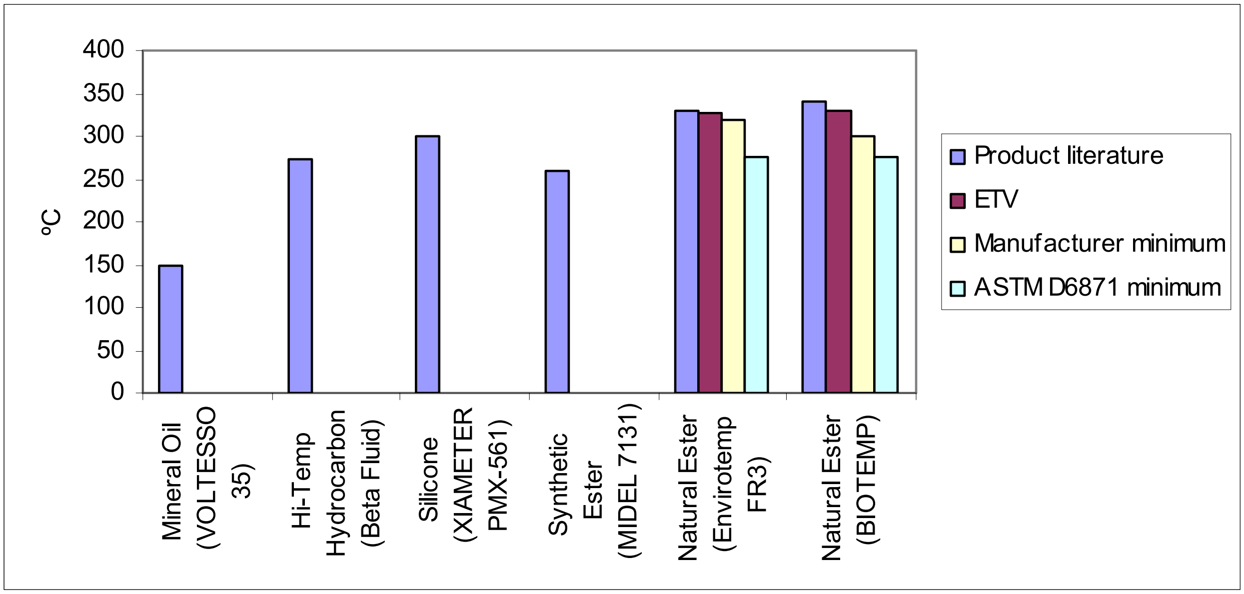


Figure 4-2
Virgin Fluids: Flash Point

ASTM D92 test results from Appendix A (Table A-2) and Appendix D

ETV—Environmental Technology Verification

ASTM D6871—*Standard Specification for Natural (Vegetable Oil) Ester Fluids Used in Electrical Apparatus* (Appendix C)

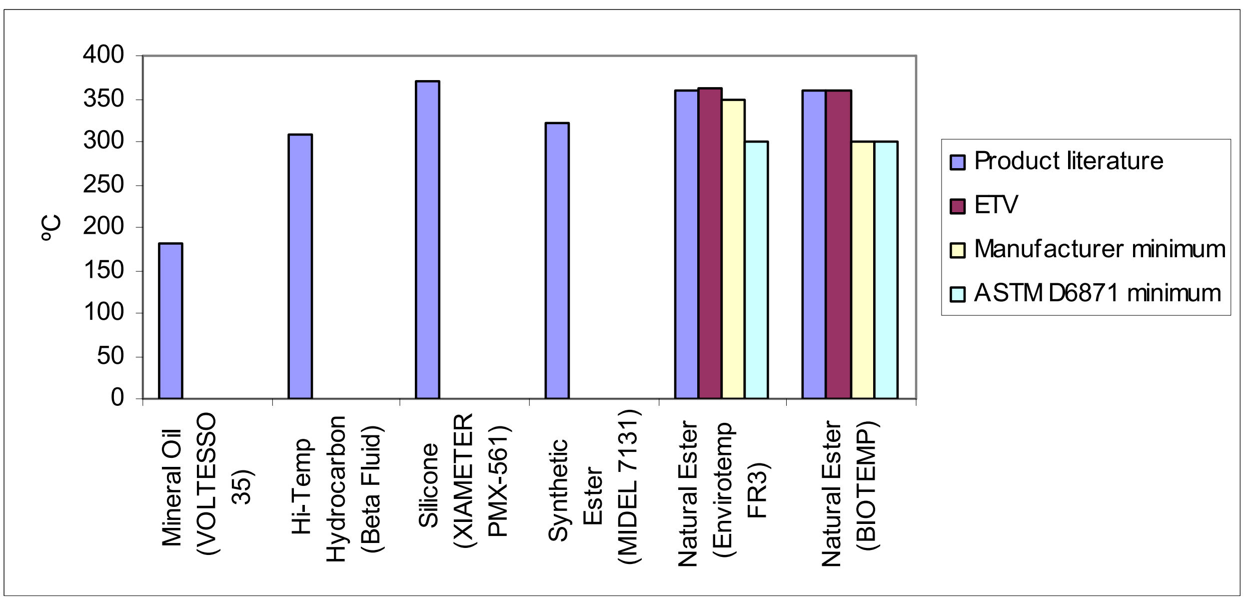


Figure 4-3
Virgin Fluids: Fire Point

ASTM D92 test results from Appendix A (Table A-2) and Appendix D

ETV—Environmental Technology Verification

ASTM D6871—*Standard Specification for Natural (Vegetable Oil) Ester Fluids Used in Electrical Apparatus* (Appendix C)

Two nationally recognized laboratories—Underwriters Laboratories (UL®) and Factory Mutual Research Corporation (FM™)—test and classify transformer fluids. Fluids with fire points below 300 ºC are classified as flammable. Thus, UL classifies VOLTESSO 35 mineral oil as a flammable transformer fluid and FM approves it for use under specific conditions that take this classification into account. UL classifies all other fluids shown in Figure 4-3 as less flammable and FM approves their use accordingly.

The two virgin natural ester fluids (Envirotemp FR3 and BIOTEMP) subjected to Environmental Technology Verification tests have flash and fire points in close agreement with values published in their product literature. These fluids also exceed the minimum flash and fire points specified by ASTM D6871 *Standard Specification for Natural (Vegetable Oil) Ester Fluids Used in Electrical Apparatus* and by their manufacturers.

In-Service Natural Ester Fluids

Natural ester fluids tested after a service period of at least 1 year (Figures 4-4 and 4-5) exceed their manufacturers' minimum flash and fire points. They also match or exceed the minimum fire point specified by IEEE C57.147 *IEEE Guide for Acceptance and Maintenance of Natural Ester Fluids in Transformers.*

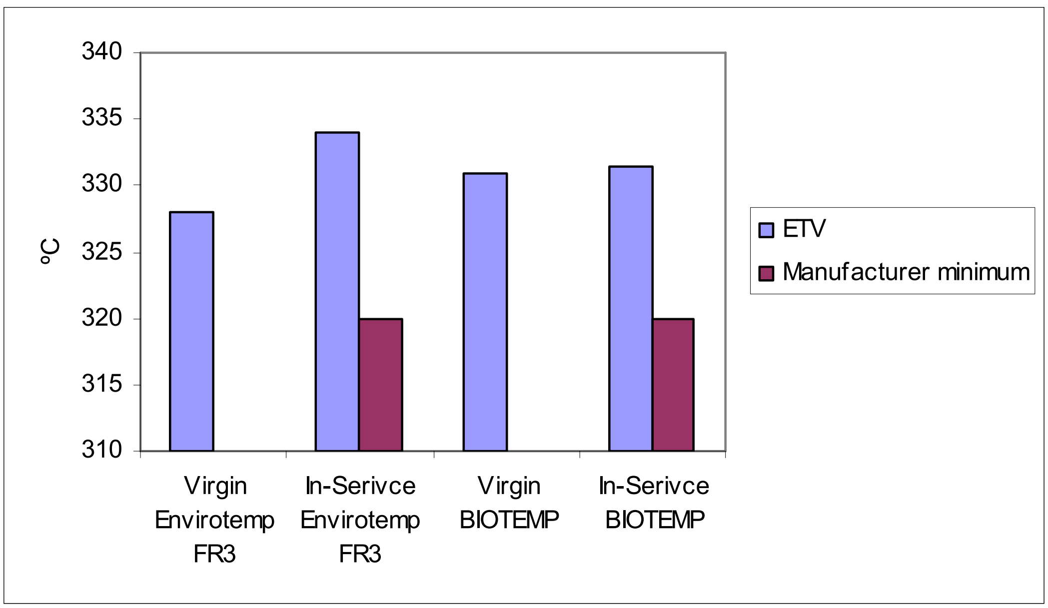


Figure 4-4
In-Service and Virgin Natural Ester Fluids: Flash Point

ASTM D92 test results from Appendix A (Table A-2); some values were unavailable
ETV—Environmental Technology Verification

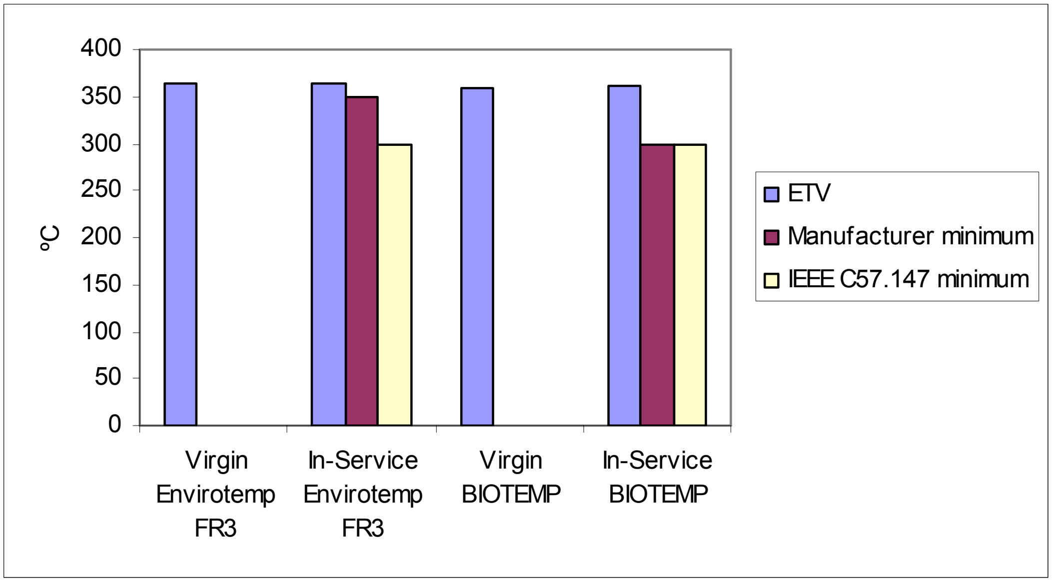


Figure 4-5
In-Service and Virgin Natural Ester Fluids: Fire Point

ASTM D92 test results from Appendix A (Table A-2); some values were unavailable

ETV—Environmental Technology Verification

IEEE C57.147—*IEEE Guide for Acceptance and Maintenance of Natural Ester Fluids in Transformers* for transformer voltage class ≤ 69 kV (Appendix C)

Operational Impacts

Shipping, Handling, and Storage

U.S. Department of Transportation (DOT) regulations to govern safe transport use flash point to define flammable and combustible materials. Purchasers of fluid-filled transformers or bulk transformer fluids should consult these regulations to ensure compliance. Less flammable fluids will require fewer safety precautions and may be less costly to ship, handle, and store than flammable mineral oil.

If transformer fluids do ignite during handling, workers may be exposed to excess heat, smoke, and chemical emissions. For example, UL found that a high-molecular-weight hydrocarbon fluid released 10 times more heat and 5 times more carbon monoxide during combustion than Dow Corning 561 silicone fluid. On the other hand, ABB claims that BIOTEMP natural ester fluid releases only carbon dioxide and water if it burns completely and MIDEL 7131 synthetic ester fluid apparently poses no more danger than wood smoke, if ignited.

Transformer fluid manufacturers publish MSDSs describing the properties of their products and procedures for handling them in a safe manner. MSDSs include data on physical properties (such as flash and fire point), toxicity, health effects, first aid, reactivity, storage, disposal, protective equipment, and procedures for handling spills.

Installation

The National Electrical Safety Code (NESC®) published by the Institute of Electrical and Electronics Engineers (IEEE) outlines basic rules for safeguarding workers during transformer installation, operation, and maintenance. Clearly, working with flammable transformer fluids demands more workplace safety precautions than working with less flammable fluids. Enhanced safety precautions add to the cost of choosing flammable transformer fluids.

In the United States, fluid-filled transformer installations must meet the requirements of the National Electrical Code (NEC®), published by the National Fire Protection Association (NFPA). This code incorporates conditions for the use of transformer fluids specified by UL and FM. Fluid-filled transformer installations must comply with local building codes as well.

NEC requires the use of fire safeguards for transformer installations, including:

- minimum clearances between transformers and buildings or construction materials,
- fire walls or vaults,
- automatic sprinklers, and
- basins to contain potential fluid spills.

FM publishes data sheets describing these requirements in detail for indoor and outdoor installations—depending on the power rating of the transformer, the volume of fluid in the transformer, and the fire classification of the fluid.

Transformers filled with flammable fluids are subject to the most stringent installation requirements. However, NEC relaxes these requirements for transformers filled with approved less flammable fluids. Companies typically install such transformers in locations where fire safety is a primary concern—for example, beside structures or walkways, on rooftops, inside buildings, within vaults, or outdoors near ecologically sensitive areas such as forests.

By choosing less flammable transformer fluids, companies may avoid substantial transformer installation or retrofit costs. For example, NEC requirements for these fluids may allow them to dispense with fire walls or vaults, sprinklers, and containment basins while fitting transformers into tighter spaces.

Operation and Maintenance

Table 4-2 displays provisional flash point values that should trigger prompt additional investigation of service-aged natural ester fluids, according to IEEE C57.147 *IEEE Guide for Acceptance and Maintenance of Natural Ester Fluids in Transformers.*

Table 4-2
Service-Aged Natural Ester Fluids: Provisional Flash Point Values Triggering Prompt Investigation

Transformer Voltage Class	ASTM D92, °C
≤ 69 kV	275 maximum
> 69 kV < 230 kV	275 maximum
230 kV and above	275 maximum

Because many in-service distribution and power transformers have exceeded their original life expectancies, fire safety is a growing concern in North American systems. Retrofilling these transformers with high flash- and fire-point fluids may allow them to remain in service while "running hot," thus extending their useful life in a safe manner.

During retrofill, it is important to note that residual concentrations of mineral oil can lower the fire point of the replacement fluid below 300 ºC. According to product literature, this occurs when the residual concentration of mineral oil is greater than 10% of the weight for BIOTEMP natural ester fluid and 7% of the weight for Envirotemp FR3 natural ester fluid.

Using less flammable transformer fluids significantly reduces the risk of transformer explosions and fires accompanied by property loss. Reduced risk mitigates fire liability and lowers insurance premiums.

Recovery and Reuse

Depending on how much fluid diagnostic properties change during service, transformer fluids can be reconditioned (filtered and degassed), reclaimed (Fullers earth treatment), or drained (discarded) and refilled.

Some companies use discarded fluids for waste-to-energy conversion. One company responding to EPRI's 2009 survey noted that the high flash point of Envirotemp FR3 natural ester fluid resulted in low energy (Btu) output during the conversion process. Presumably, this would also be true of other transformer fluids with high flash points.

Cleanup

Thousands of gallons of water may be needed to extinguish fires in transformer vaults installed below street level. To help avoid costly cleanup of contaminated water, companies can use less flammable fluids in underground transformer installations.

Pour Point

Measured Values

Pour point is the lowest temperature at which a transformer fluid will just flow under conditions of normal use. Transformer fluids function best with very low pour points. Standard test method ASTM D97 is used to test this property.

Virgin Fluids

Test results reported in the product literature (Figure 4-6) show that virgin VOLTESSO 35 mineral oil, XIAMETER PMX-561 silicone fluid, and MIDEL 7131 synthetic ester fluid pour freely at temperatures as low as -55 to -62 ºC. On the other hand, Beta Fluid high-temperature hydrocarbon fluid and the two natural ester fluids (Envirotemp FR3 and BIOTEMP) stop pouring freely at -20 to -25 ºC.

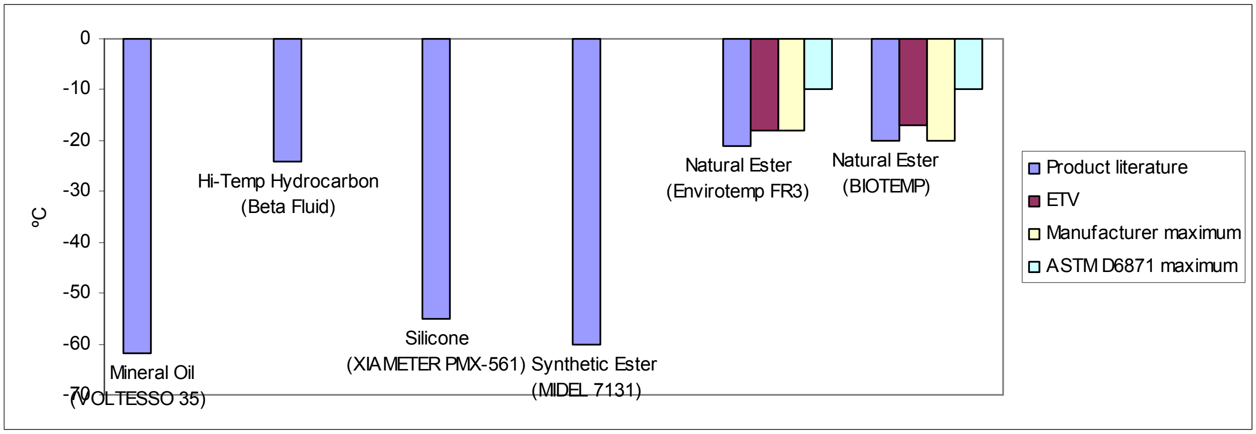


Figure 4-6
Virgin Fluids: Pour Point

ASTM D97 test results from Appendix A (Table A-2) and Appendix D

ETV—Environmental Technology Verification

ASTM D6871—*Standard Specification for Natural (Vegetable Oil) Ester Fluids Used in Electrical Apparatus* (Appendix C). The maximum is defined as the "lowest temperature to which the material may be cooled without seriously limiting the degree of circulation."

Environmental Technology Verification tests of the two natural ester fluids (Envirotemp FR3 and BIOTEMP) document pour points slightly less favorable than those published in their product literature. However, both fluids meet the pour point standards set by their manufacturers and exceed the -10 ºC pour point standard set by ASTM D6871 *Standard Specification for Natural (Vegetable Oil) Ester Fluids Used in Electrical Apparatus.*

In-Service Natural Ester Fluids

Environmental Technology Verification tests of pour point were not conducted for in-service natural ester fluids.

Operational Impacts

Shipping, Handling, and Storage

One company surveyed by EPRI in 2009 noted that each drum or tote used to ship virgin or used Envirotemp FR3 natural ester fluid must have a container head space blanketed with nitrogen.

The same company observed that Envirotemp FR3 thickens into a gel when stored for long periods at temperatures at or below 5 ºF (-15 ºC). The IEEE C57.147 *IEEE Guide for Acceptance and Maintenance of Natural Ester Fluids in Transformers* corroborates this observation, stating that "it is possible for the pour point of natural esters to increase after long-standing times at low temperatures" (IEEE C57.147 2008).

A second company concurred, saying that they needed to move transformers inside to loosen up the fluid before installing them in the winter. According to these users, if Envirotemp FR3 must be stored outdoors in cold climates, then the fluid-filled drums or totes should be placed on their sides, with the bung below fluid level, and protected by a tent. Special storage provisions may add to the cost of natural ester fluids.

Operation and Maintenance

The higher pour points of natural ester fluids may make them less desirable for use in cold climates. One operating challenge for transformers filled with these fluids is the “cold start,” which occurs when frozen transformers are re-energized at full load. ABB tested distribution transformers filled with BIOTEMP natural ester fluid under cold start conditions. They cooled 25 kVA, 12.5/7.2 kV transformers to -70 ºC, solidifying the transformer fluid. When re-energized at full load, the transformers performed normally as they warmed to a full operating temperature of 65 ºC and the frozen BIOTEMP liquified. ABB attributes this success to its claim that BIOTEMP retains its insulating and cooling properties when solidified, and that its constituents freeze and thaw at different temperatures, promoting gradual change.

Another operating challenge for transformers filled with natural ester fluids is the fact that mechanical parts do not move well in fluid that gels in the cold. As one EPRI survey respondent noted, this is not an issue for energized transformers, but may require modified procedures to get switches and pumps working properly during a cold start. CPS reported no field problems for transformers filled with Envirotemp FR3 natural ester fluid during the extremely cold winter months of 2008–2009.

The Environmental Technology Verification tests of BIOTEMP natural ester fluid reported above used fluid samples that did not contain a pour point depressant. But ABB notes that small quantities of polyvinyl acetate or acrylic additives can drive the pour point of BIOTEMP down to -25 ºC.

Another strategy to lower the pour point of natural ester fluids would be to blend them with mineral oil. This strategy would be particularly attractive when natural ester fluids are used to retrofill transformers formerly operating with mineral oil.

Recovery and Reuse

One company using Envirotemp FR3 natural ester fluid told EPRI that the market for recycled fluid is small and they have not generated any revenue from recycling. Most used oil vendors have been slow to switch their industrial processes to accommodate used natural ester fluids because small economies of scale make it commercially infeasible. In one proposal—so far not implemented—CPS would buy back used Envirotemp FR3 for feedstock in its production process.

Kinematic Viscosity

Measured Values

Viscosity describes a fluid’s resistance to flow. Kinematic viscosity, measured using standard test method ASTM D445, is the ratio of the fluid’s viscosity to its density. Fluids with lower kinematic viscosity flow more freely.

Virgin Fluids

Figure 4-7 compares the kinematic viscosities of virgin VOLTESSO 36 mineral oil and five alternate transformer fluids at three different temperatures: 100 ºC (top), 40 ºC (middle), and 0 ºC (bottom). For all fluids, kinematic viscosity increases as temperature decreases (note the change in y-axis scale from the top graph to the bottom graph).

According to data from the product literature, VOLTESSO 35 mineral oil has lower kinematic viscosity than other transformer fluids at all temperatures. Beta Fluid high-temperature hydrocarbon fluid displays interesting behavior: it has relatively high kinematic viscosity at 100 ºC but becomes much more viscous than other fluids at lower temperatures. XIAMETER PMX-561 silicone fluid displays the obverse behavior: it has the highest viscosity of all fluids at 100 ºC but becomes relatively less viscous at lower temperatures.

Natural ester fluids (Envirotemp FR3 and BIOTEMP) have moderate viscosities at the temperatures tested. According to the Envirotemp FR3 patent (McShane et al. 2003), preferred fluids have viscosities between about 2 and 15 cSt at 100 ºC, and less than about 110 cSt at 40 ºC. Both natural ester fluids meet this criterion.

In Environmental Technology Verification tests at each temperature, kinematic viscosities of both natural ester fluids fall below the maximum values specified by their manufacturers and by ASTM D6871 *Standard Specification for Natural (Vegetable Oil) Ester Fluids Used in Electrical Apparatus.*

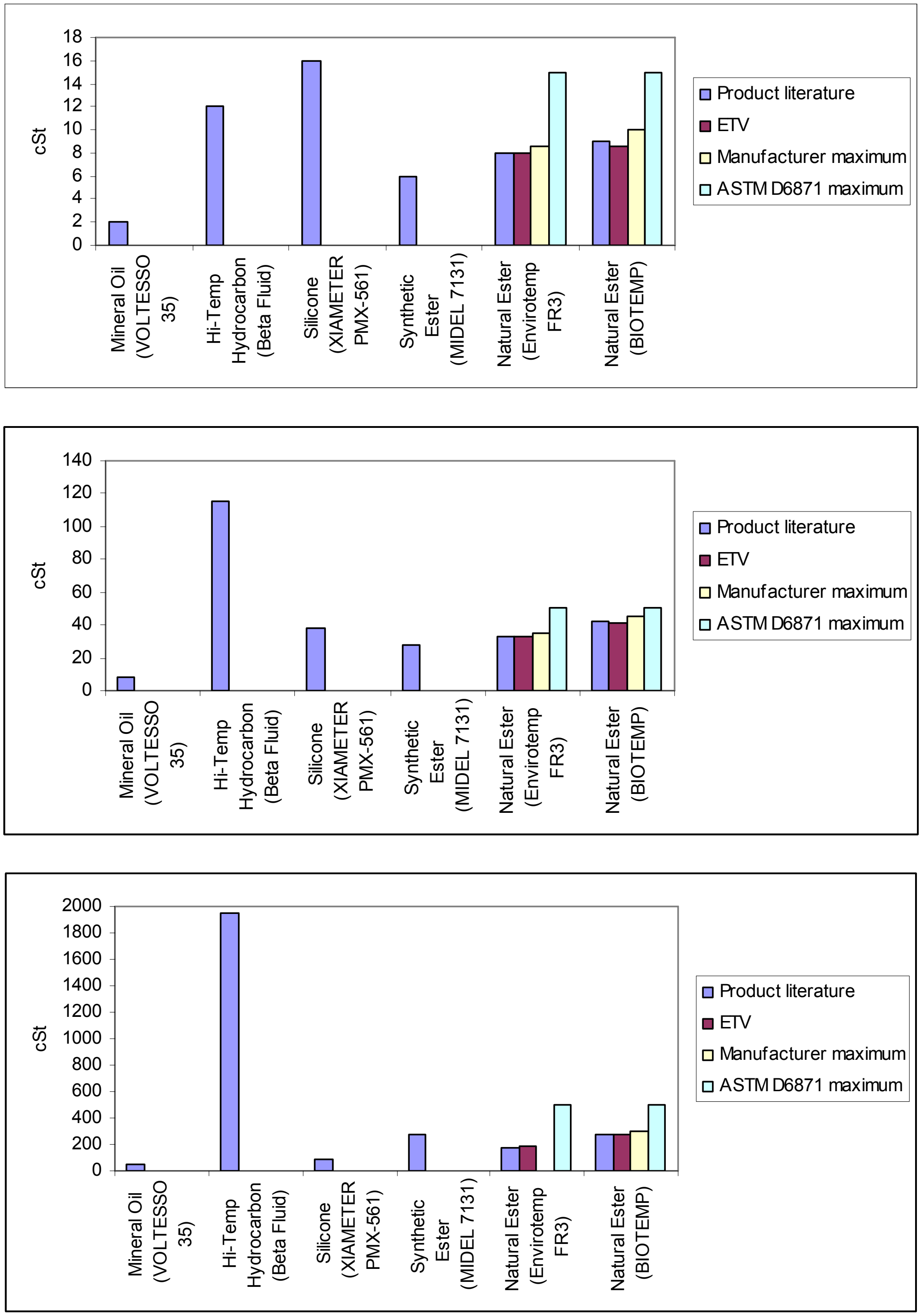


Figure 4-7
Virgin Fluids: Kinematic Viscosity (top) 100 °C, (middle) 40 °C, (bottom) 0 °C

ASTM D445 test results from Appendix A (Table A-2) and Appendix D; some values were unavailable
ETV—Environmental Technology Verification
ASTM D6871—*Standard Specification for Natural (Vegetable Oil) Ester Fluids Used in Electrical Apparatus* (Appendix C)
Note the change in y-axis scale from the top graph to the bottom graph

In-Service Natural Ester Fluids

Environmental Technology Verification tests of kinematic viscosity were not conducted for in-service natural ester fluids.

Operational Impacts

Shipping, Handling, and Storage

Like pour point, viscosity is a temperature-dependent property that causes fluids to exhibit decreased utility at lower temperatures. Fluids such as natural esters that gel below -20 ºC and become very viscous around 0 ºC require special handling. For example, outdoor storage at low temperatures for long periods of time is not recommended for natural ester fluids and it may be necessary to warm chilled fluids before using them.

Operation and Maintenance

Equipment designers use viscosity to confirm that a transformer fluid will retain its fluidity over the temperature operating range of transformers and associated electrical equipment. As viscosity increases with age or oxidation in natural ester fluids such as Envirotemp FR3 or BIOTEMP, heat transfer decreases. This means that transformers need cooling systems (more radiators, higher capacity pumps, wider cooling ducts) adequate to handle the burden imposed by aging natural ester fluids. Fluid viscosity issues related to aging are more pressing for transformers filled with natural ester fluids than for those filled with comparatively less-viscous mineral oil.

As noted above, increasing viscosity may indicate excessive oxidation of aging natural ester fluids. Thus, viscosity measurements should be part of the diagnostic test routine for transformers filled with these fluids. Table 4-3 displays provisional kinematic viscosity values that should trigger prompt additional investigation of service-aged natural ester fluids, according to IEEE C57.147 *IEEE Guide for Acceptance and Maintenance of Natural Ester Fluids in Transformers.*

Table 4-3
Service-Aged Natural Ester Fluids: Provisional Kinematic Viscosity Values Triggering Prompt Investigation

Transformer Voltage Class	ASTM D445 at 40 ºC, %
≤ 69 kV	10 minimum
> 69 kV < 230 kV	10 minimum
230 kV and above	10 minimum

Best practice suggests that companies use transformer fluids of the lowest compatible viscosity for retrofill applications.

Cleanup

In the event of a fluid spill, transformer fluids with higher viscosities at ambient temperatures have the advantage of slower surface and subsurface migration.

Heat Capacity

Measured Values

Heat capacity, or specific heat, measures the amount of energy necessary to produce a unit change of temperature in a unit mass of transformer fluid. Fluids with higher heat capacity are better coolants. Standard test method ASTM D2766 is used to measure heat capacity.

Virgin Fluids

According to values from the product literature shown in Figure 4-8, VOLTESSO 35 mineral oil, Beta Fluid high-temperature hydrocarbon fluid, and Envirotemp FR3 natural ester fluid have similar heat capacities. BIOTEMP natural ester fluid has a clear advantage with respect to this property, while XIAMETER PMX-561 falls a bit short.

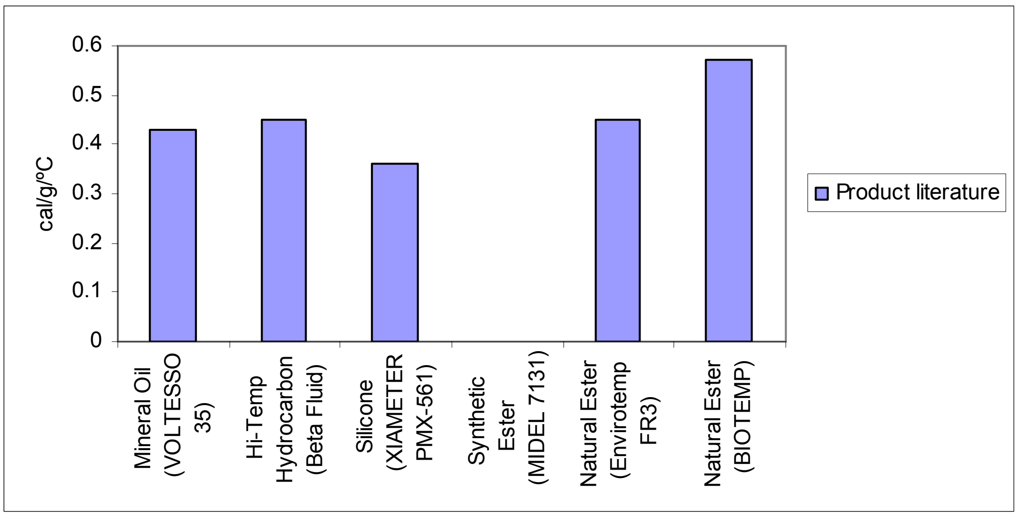


Figure 4-8
Virgin Fluids: Heat Capacity (Specific Heat), 25 ºC

ASTM D2766 test results from Appendix D; some values were unavailable

ASTM D6871 *Standard Specification for Natural (Vegetable Oil) Ester Fluids Used in Electrical Apparatus* suggests 0.53 cal/g/ºC at 20 ºC as a typical heat capacity value for natural ester fluids; this is not a mandatory standard.

Environmental Technology Verification tests of heat capacity were not conducted for virgin natural ester fluids.

In-Service Natural Ester Fluids

Environmental Technology Verification tests of heat capacity were not conducted for in-service natural ester fluids.

Operational Impacts

Operation and Maintenance

Engineers use transformer fluid heat capacity to calculate how a transformer may react to thermal stress.

With its higher heat capacity, the temperature rise of BIOTEMP natural ester fluid will be lower than the temperature rise of VOLTESSO 35 mineral oil or Envirotemp FR3 natural ester fluid for the same amount of heat loss (cooling). This makes BIOTEMP a good choice when it is necessary to operate transformers and associated equipment at higher temperatures. This need frequently arises as transformers age.

Thermal Conductivity

Measured Values

Thermal conductivity is a measure of heat transfer, as documented by standard test method ASTM D2717. Transformer fluids with high thermal conductivity are better coolants.

Virgin Fluids

Data for virgin transformer fluids taken from the product literature (Figure 4-9) show that both natural ester fluids (Envirotemp FR3 and BIOTEMP) have slightly higher thermal conductivity than the other fluids tested. Although ASTM D2717 data were unavailable for MIDEL 7131 synthetic ester fluid, its product literature states that its thermal conductivity is comparable to that of mineral oil.

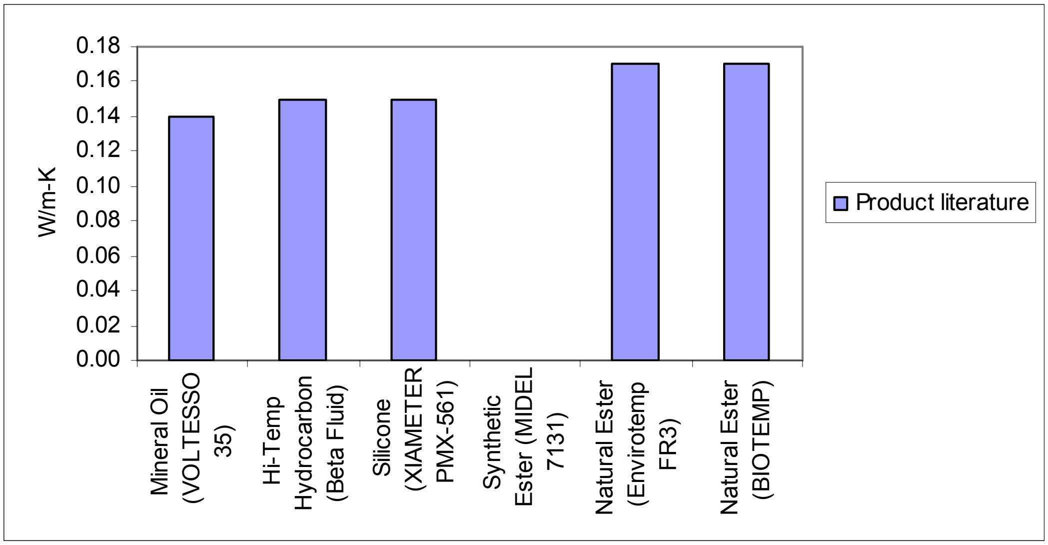


Figure 4-9
Virgin Fluids: Thermal Conductivity, 25 ºC

ASTM D2717 test results from Appendix D; some values were unavailable

ASTM D6871 *Standard Specification for Natural (Vegetable Oil) Ester Fluids Used in Electrical Apparatus* suggests 0.167 W/m-K at 20 ºC as a typical thermal conductivity value for natural ester fluids; this is not a mandatory standard.

Environmental Technology Verification tests of thermal conductivity were not conducted for virgin natural ester fluids.

In-Service Natural Ester Fluids

Environmental Technology Verification tests of thermal conductivity were not conducted for in-service natural ester fluids.

Operational Impacts

Operation and Maintenance

Engineers use transformer fluid thermal conductivity, along with heat capacity, to calculate how a transformer may react to thermal stress.

The higher thermal conductivity of Envirotemp FR3 and BIOTEMP natural ester fluids make them good choices when it is necessary to operate transformers and associated equipment at higher temperatures. This need frequently arises as transformers age.

Relative Density

Measured Values

The relative density of a transformer fluid is measured with respect to water, which acts as a reference fluid assigned a value of 1.0. Ideal fluids are less dense than water. Relative density (also called specific gravity) is measured using standard test method ASTM D1298.

Virgin Fluids

As shown in Figure 4-10, all virgin transformer fluids tested have relative densities less than 1.0, indicating that they will float on water. Both Envirotemp FR3 and BIOTEMP natural ester fluids have relative densities resembling that of VOLTESSO 35 mineral oil. Their densities fall below the maximum value established for natural ester fluids by ASTM D6871 *Standard Specification for Natural (Vegetable Oil) Ester Fluids Used in Electrical Apparatus.* XIAMETER PMX-561 silicone fluid and MIDEL 7131 synthetic ester fluid have relative densities approaching that of water.

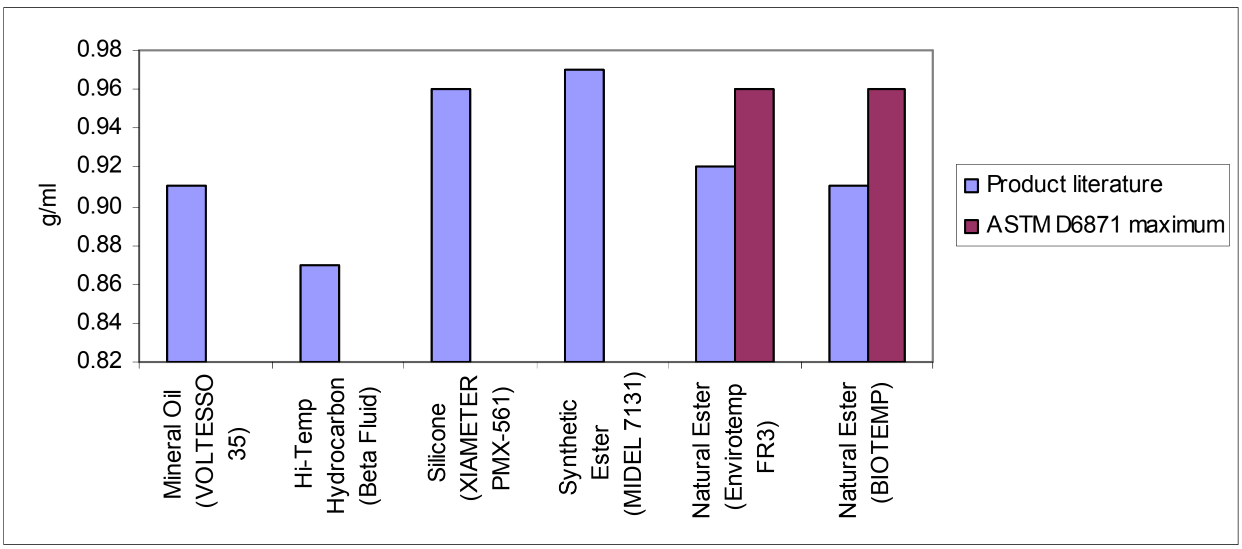


Figure 4-10
Virgin Fluids: Relative Density, 15 °C

ASTM D1298 test results from Appendix D
ASTM D6871—*Standard Specification for Natural (Vegetable Oil) Ester Fluids Used in Electrical Apparatus* (Appendix C)

Environmental Technology Verification tests of relative density were not conducted for virgin natural ester fluids.

In-Service Natural Ester Fluids

Environmental Technology Verification tests of relative density were not conducted for in-service natural ester fluids.

Operational Impacts

Shipping, Handling, and Storage

During custody transfer, personnel use relative density to convert measured fluid volumes to volumes at standard reference temperatures. Relative density is an important indicator of transformer fluid quality. In addition, it may affect fluid handling and storage since higher temperatures generally decrease relative density.

Operation and Maintenance

For acceptable performance, a transformer fluid must have a relative density sufficient for effective heat transfer. All of the fluids tested meet this criterion.

Coefficient of Thermal Expansion

Measured Values

Standard test method ASTM D1903 measures the thermal expansion coefficient of transformer fluids. This coefficient describes how a fluid's volume changes as temperature changes while pressure remains constant. Ideal transformer fluids have low coefficients of thermal expansion.

Virgin Fluids

Data from the product literature (Figure 4-11) show little variation in coefficients of thermal expansion for the virgin transformer fluids tested over a temperature range of 25–100 ºC. The exception is XIAMETER PMX-561 silicone fluid, which has a substantially higher value for this property.

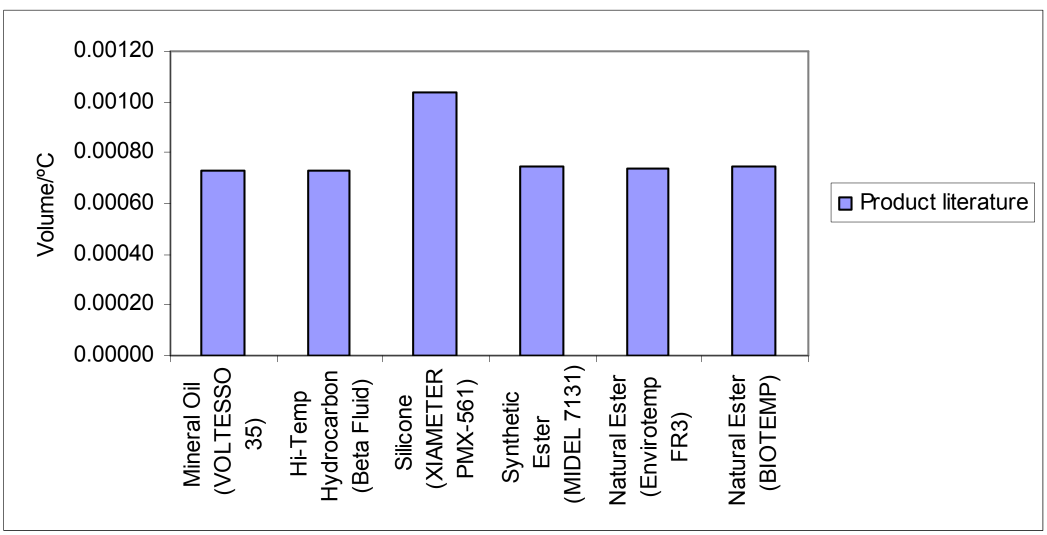


Figure 4-11
Virgin Fluids: Coefficient of Thermal Expansion, 25–100 ºC

ASTM D1903 test results from Appendix D

ASTM D6871 *Standard Specification for Natural (Vegetable Oil) Ester Fluids Used in Electrical Apparatus* suggests 0.00075 volume/ºC as a typical value for natural ester fluids; this is not a mandatory standard.

Environmental Technology Verification tests of the coefficient of thermal expansion were not conducted for virgin natural ester fluids.

In-Service Natural Ester Fluids

Environmental Technology Verification tests of the coefficient of thermal expansion were not conducted for in-service natural ester fluids.

Operational Impacts

Shipping, Handling, and Storage

Engineers use the thermal expansion coefficient to compute the container (or transformer) size needed to accommodate changes in transformer fluid volume over the full range of temperatures encountered in shipping, handling, storage, and use. Since XIAMETER PMX-561 silicone fluid has the highest thermal expansion coefficient, its use may require special procedures.

5

DIELECTRIC PROPERTIES OF TRANSFORMER FLUIDS AND THEIR OPERATIONAL IMPACTS

This section compares transformer fluid performance on an array of dielectric properties including dielectric breakdown, dissipation (power) factor, gassing tendency, volume resistivity, and relative permittivity.

Dielectric Breakdown Voltage

Measured Values

Dielectric breakdown voltage is the minimum voltage at which a transformer fluid begins to conduct electricity—that is, to lose its insulating properties. It is a measure of the fluid's ability to withstand high electric field stress. Adequate dielectric breakdown voltage (also called dielectric strength) is an essential property of transformer fluids.

ASTM D877 and ASTM D1816 are two standard test methods used to measure AC dielectric breakdown voltage. Both methods measure the minimum voltage required to cause arcing between two electrodes submerged in a transformer fluid. However, they are used for different purposes, as discussed under Operational Impacts below. ASTM D3300 measures impulse dielectric breakdown voltage under transient voltage stresses similar to those imposed by lightning or power surges.

Virgin Fluids

Figure 5-1 displays results from ASTM D877 tests of virgin transformer fluids. According to the product literature, Envirotemp FR3 and BIOTEMP natural ester fluids have minimum dielectric breakdown voltages similar to that of VOLTESSO 35 mineral oil, while values for XIAMETER PMX-561silicone fluid and MIDEL 7131 synthetic ester fluid are somewhat lower. Beta Fluid high-temperature hydrocarbon fluid has the highest dielectric breakdown voltage on this test.

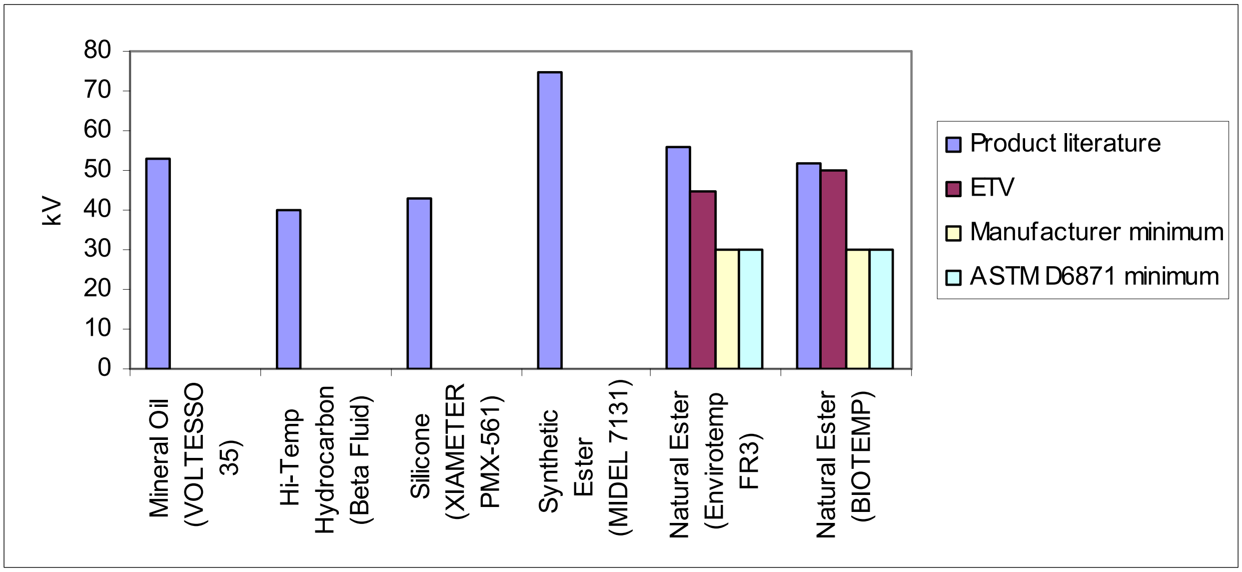


Figure 5-1
Virgin Fluids: Dielectric Breakdown Voltage (Minimum)

ASTM D877 test results from Appendix A (Table A-2) and Appendix D

ETV—Environmental Technology Verification

ASTM D6871—*Standard Specification for Natural (Vegetable Oil) Ester Fluids Used in Electrical Apparatus* (Appendix C)

Note that synthetic ester minimum dielectric breakdown voltage is determined by standard method IEC 60814, an international test method commonly used in Europe where MIDEL 7131 is largely employed; IEC and ASTM standard methods may differ.

Results of ASTM D1816 tests, graphed in Figure 5-2, show Envirotemp FR3 and BIOTEMP natural ester fluids with superior 1-mm gap dielectric breakdown voltages compared with VOLTESSO 35 mineral oil and Beta Fluid high-temperature hydrocarbon fluid. The converse is true for results of ASTM D3300 tests (Figure 5-3), where both natural ester fluids have lower impulse breakdown voltages than VOLTESSO 35 mineral oil and Beta Fluid high-temperature hydrocarbon fluid.

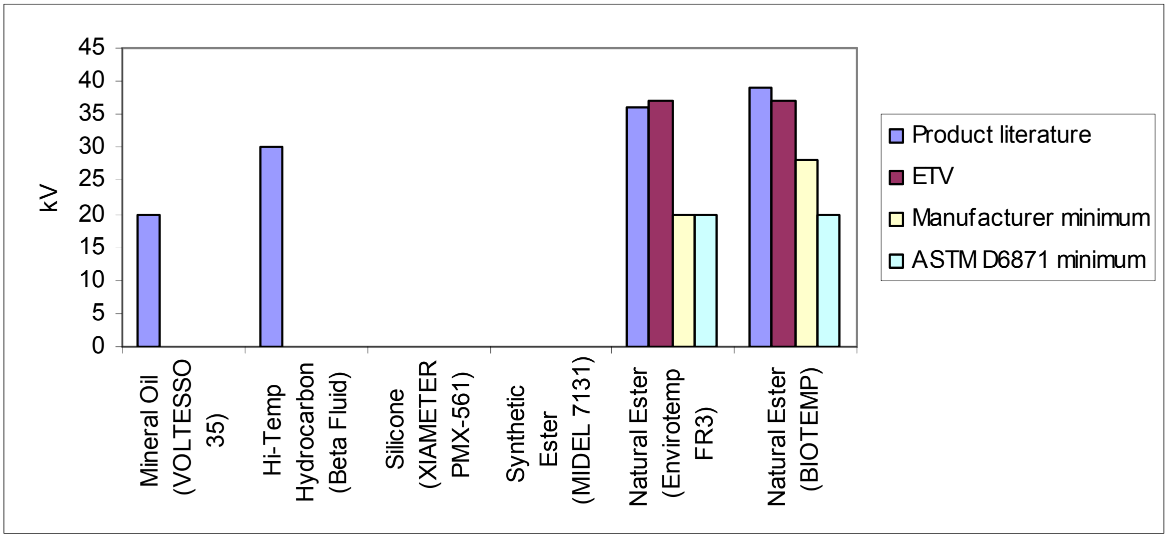


Figure 5-2
Virgin Fluids: Dielectric Breakdown Voltage (1-mm Gap)

ASTM D1816 test results from Appendix A (Table A-2) and Appendix D; some values were unavailable

ETV—Environmental Technology Verification

ASTM D6871—*Standard Specification for Natural (Vegetable Oil) Ester Fluids Used in Electrical Apparatus* (Appendix C)

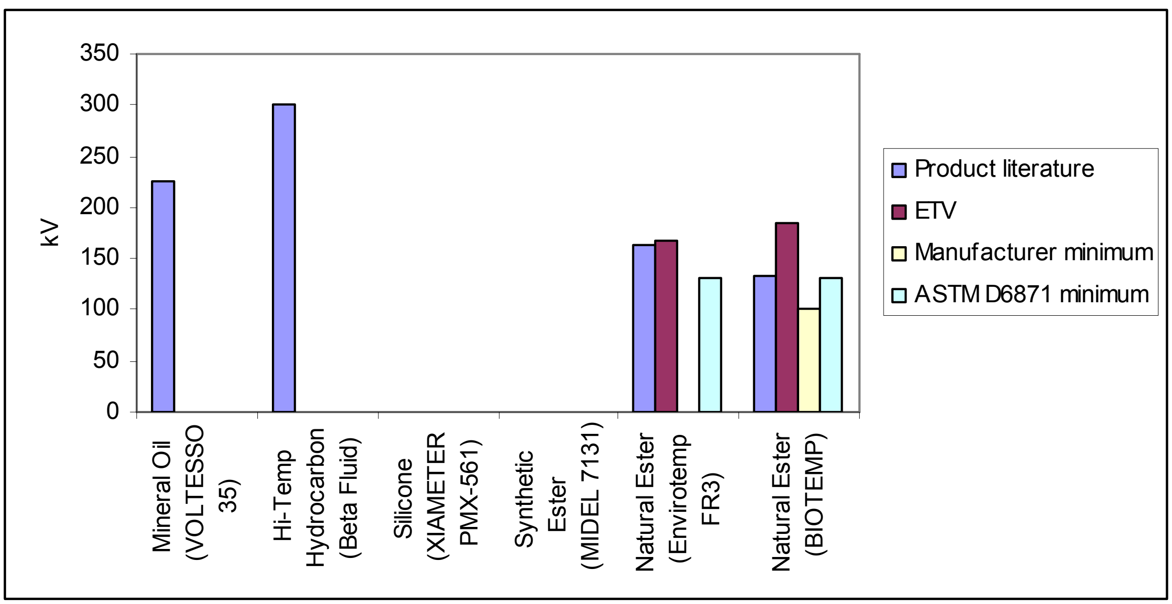


Figure 5-3
Virgin Fluids: Dielectric Breakdown Voltage (Impulse), 25 °C

ASTM D3300 test results from Appendix A (Table A-2) and Appendix D; some values were unavailable

ETV—Environmental Technology Verification

ASTM D6871—*Standard Specification for Natural (Vegetable Oil) Ester Fluids Used in Electrical Apparatus* (Appendix C)

In Environmental Technology Verification tests, both virgin natural ester fluids exceed the minimum dielectric breakdown voltage specified by their manufacturers and ASTM D6871 *Standard Specification for Natural (Vegetable Oil) Ester Fluids Used in Electrical Apparatus* for minimum and 1-mm gap tests (Figures 5-1 and 5-2).

Envirotemp FR3 and BIOTEMP natural ester fluids also exceed the minimum impulse breakdown voltage set by ASTM D6871 *Standard Specification for Natural (Vegetable Oil) Ester Fluids Used in Electrical Apparatus*. BIOTEMP exceeds ABB's minimum; CPS does not specify a minimum impulse breakdown voltage for virgin Envirotemp FR3 natural ester fluid, but quotes a typical performance range of 130 to 170 kV.

In-Service Natural Ester Fluids

Environmental Technology Verification tests of dielectric breakdown voltage were not conducted for in-service natural ester fluids. However, IEEE C57.147 *IEEE Guide for Acceptance and Maintenance of Natural Ester Fluids in Transformers* sets the gap dielectric breakdown voltage limits for service-aged fluids shown in Table 5-1.

Table 5-1
Service-Aged Natural Ester Fluids: Gap Dielectric Breakdown Voltage Limits

Property	Unit	Test Method	Gap	Transformer Voltage Class		
				≤ 69 kV	> 69 kV < 230 kV	≥ 230 kV
Delectric Breakdown Voltage	kV	ASTM D1816	1-mm	23 minimum	28 minimum	30 minimum
			2-mm	40 minimum	47 minimum	50 minimum

Operational Impacts

Shipping, Handling, and Storage

Moisture and particles present in transformer fluids lower their dielectric breakdown voltage. Companies should employ shipping, handling, and storage procedures that minimize these contaminants, which cause arcing that can damage transformer cores or windings.

ASTM D877 is suitable for acceptance testing of as-received, unprocessed transformer fluids. A low dielectric breakdown voltage on this test may indicate the presence of water or particle contaminants, but a high value does not rule them out since the test is insensitive to low contaminant concentrations.

Using ASTM D877, ABB evaluated the effect of moisture on the dielectric breakdown voltage of BIOTEMP natural ester fluid and mineral oil at room temperature (25 ºC). For a given dielectric breakdown voltage, ABB personnel observed that the performance of BIOTEMP containing 100 ppm moisture was equivalent to the performance of mineral oil containing 5 ppm moisture. In other words, BIOTEMP maintained dielectric strength at higher levels of moisture than mineral oil did. ABB suggests that this is so because BIOTEMP can hold up to 1100 ppm of moisture at room temperature. This finding may make it less important to protect BIOTEMP from moisture contamination during shipping, handling, and storage.

ASTM D3300 is suitable for acceptance testing of as-received, unprocessed transformer fluids. It is particularly sensitive to the presence of polyaromatic hydrocarbon molecules that can facilitate arcing during electrical impulse events. This test is useful for evaluating the consistency of fluid composition from shipment to shipment.

Installation

Given the lower impulse dielectric breakdown voltage of natural ester fluids compared with mineral oil, transformers filled with these fluids may require extra surge protection at additional installation cost.

Operation and Maintenance

ASTM D1816 is suitable for testing filtered, degassed, and dehydrated fluids while filling or retrofilling transformers. Both ASTM D1816 and ASTM D3300 can be used as diagnostic tests for in-service transformer fluid samples. For example, fluid impulse dielectric breakdown voltage (ASTM D3300) can be substantially lowered by service aging, contact with construction materials, or introduction of other impurities in the field.

Dissipation (Power) Factor

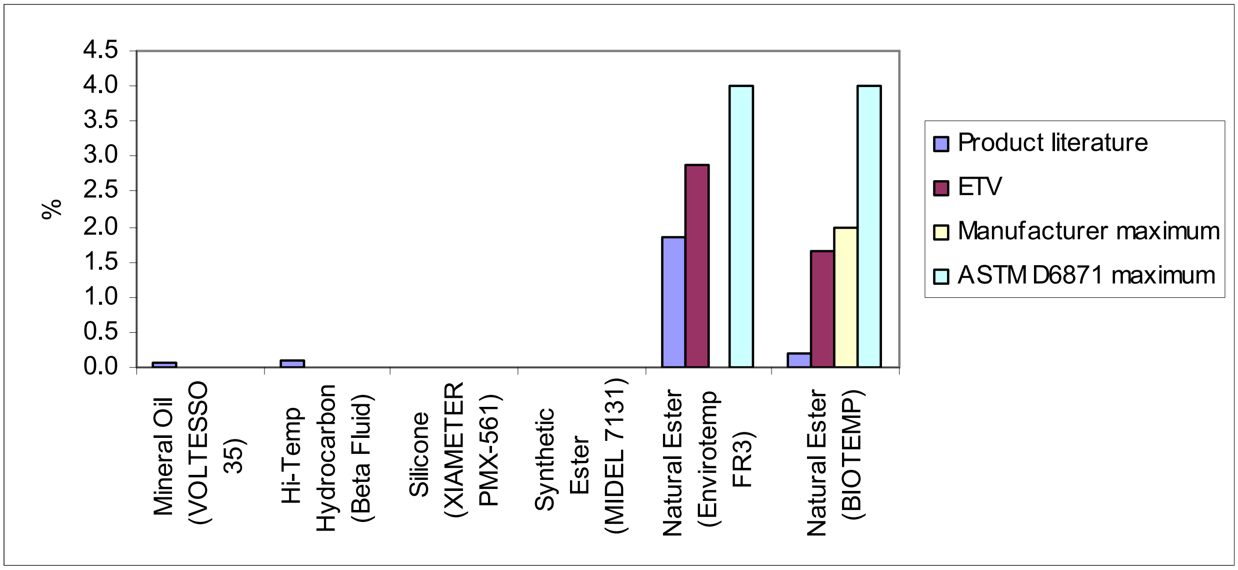
Measured Values

The dissipation (power) factor is a measure of dielectric loss, or the dissipation of energy that goes into heating a transformer fluid in an alternating electric field. Ideally, a fluid's dissipation factor should be as low as possible to prevent heating that deteriorates insulation over time. Standard test method ASTM D924 is used to test this property.

Virgin Fluids

Figure 5-4 displays results from ASTM D924 tests of virgin transformer fluids. As expected, the dissipation factor is much higher for fluids tested at 100 ºC (top graph) than for fluids tested at 25 ºC (bottom graph—note scale change). At both temperatures, natural ester fluids have higher dissipation factors than VOLTESSO 35 mineral oil. IEEE C57.147 *IEEE Guide for Acceptance and Maintenance of Natural Ester Fluids in Transformers* states that natural ester fluids have naturally higher dissipation factors than mineral oils.

In Environmental Technology Verification tests, BIOTEMP natural ester fluid has lower dissipation factors than Envirotemp FR3 natural ester fluid (reflecting different fluid chemistries)—but values for both fluids fall below the ASTM D6871 *Standard Specification for Natural (Vegetable Oil) Ester Fluids Used in Electrical Apparatus* limit. Where Environmental Technology Verification test values exceed standards set by natural ester fluid manufacturers (for example, BIOTEMP at 25 ºC), CalEPA/DTSC hypothesizes that the higher dissipation factors may reflect fluid contamination.



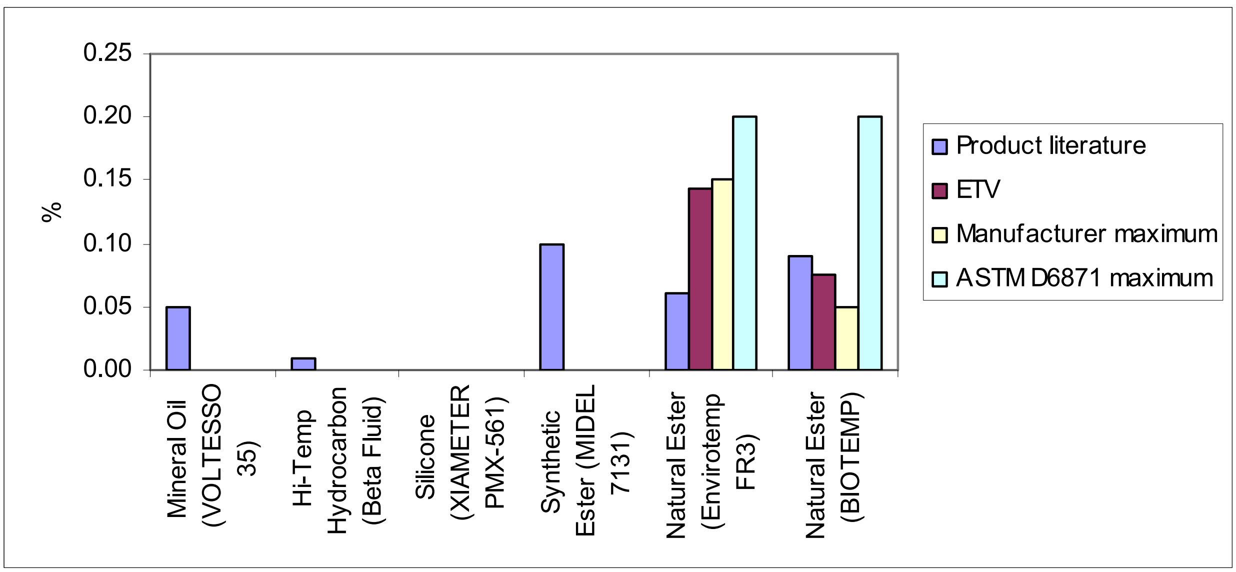


Figure 5-4
Virgin Fluids: Dissipation Factor (top) 100 °C, (bottom) 25 °C

ASTM D924 test results from Appendix A (Table A-2) and Appendix D; some values were unavailable

ETV—Environmental Technology Verification

ASTM D6871—*Standard Specification for Natural (Vegetable Oil) Ester Fluids Used in Electrical Apparatus* (Appendix C)

Note the change in y-axis scale from the top graph to the bottom graph

In-Service Natural Ester Fluids

In Environmental Technology Verification tests of in-service natural ester fluids (Figure 5-5), Envirotemp FR3 has a dissipation factor well below its manufacturer's specification. On the other hand, the dissipation factor for BIOTEMP is slightly above its manufacturer's specification. One BIOTEMP sample had a high dissipation factor (and an amber color unlike the light yellow of other samples), indicating possible thermal decomposition or oxidation of the fluid. Historical analysis revealed that these changes were related to overload testing of the transformer from which the sample was drawn. This sample raised the average dissipation factor for BIOTEMP above the manufacturer's maximum. There is little degradation of the fluids during 4.8 years of service.

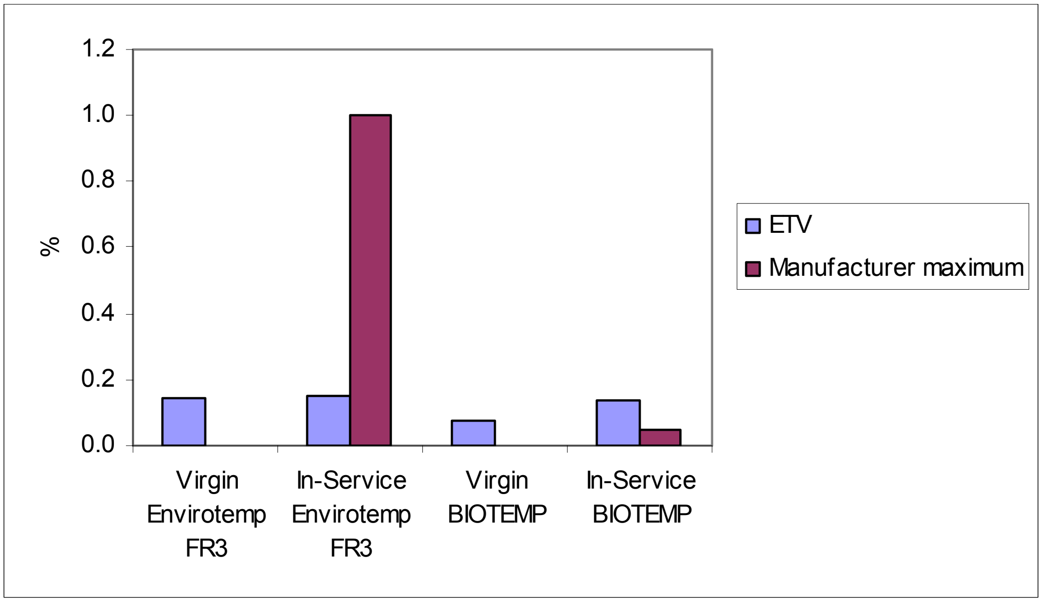


Figure 5-5
In-Service and Virgin Natural Ester Fluids: Dissipation Factor, 25 °C

ASTM D924 test results from Appendix A (Table A-2)
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Operational Impacts

Shipping, Handling, and Storage

To control product quality, companies should purchase virgin transformer fluids that meet dissipation factor specifications for fluid type—for example, specifications in the ASTM D6871 *Standard Specification for Natural (Vegetable Oil) Ester Fluids Used in Electrical Apparatus*. Dissipation factors higher than specified values likely indicate fluid degradation during handling or fluid contamination by water, dirt, or metals. Companies should employ shipping, handling, and storage procedures that minimize contamination.

Operation and Maintenance

Dissipation factor measurements are important diagnostic tools because they can signal fluid degradation with use. When the dissipation factor rises and the color changes, a transformer fluid may be contaminated or experiencing thermal decomposition or oxidation. To maintain peak performance, such fluids should be replaced. Special care should be taken to avoid introducing contaminants when topping or retrofilling transformers in the field.

Table 5-2 displays provisional dissipation factor values that should trigger prompt additional investigation of service-aged natural ester fluids, according to IEEE C57.147 *IEEE Guide for Acceptance and Maintenance of Natural Ester Fluids in Transformers.*

Table 5-2
Service-Aged Natural Ester Fluids: Provisional Dissipation Factor Values Triggering Prompt Investigation

Transformer Voltage Class	ASTM D924 at 25°C, %
≤ 69 kV	3 minimum
> 69 kV < 230 kV	3 minimum
230 kV and above	3 minimum

Gassing Tendency

Measured Values

Gassing tendency measures the rate at which a transformer fluid either releases or adsorbs hydrogen gas when the fluid undergoes enough electrical stress to cause ionization. Fluids that adsorb hydrogen gas have a negative gassing tendency, which is desirable. Standard test method ASTM D2300 is used to test this property.

Virgin Fluids

According to the product literature from fluid manufacturers, virgin natural ester fluids have a much lower gassing tendency than mineral oil (Figure 5-6). IEEE C57.147 *IEEE Guide for Acceptance and Maintenance of Natural Ester Fluids in Transformers* corroborates this, stating that natural ester fluids have naturally lower gassing tendency than mineral oils. In the figure, natural ester fluids have gassing tendencies that do not exceed zero µl/min, the ASTM D6871 *Standard Specification for Natural (Vegetable Oil) Ester Fluids Used in Electrical Apparatus* maximum for virgin fluids of this type. In contrast, Beta Fluid high-temperature hydrocarbon fluid has a positive gassing tendency of 20 µl/min, which makes it a less-desirable choice.

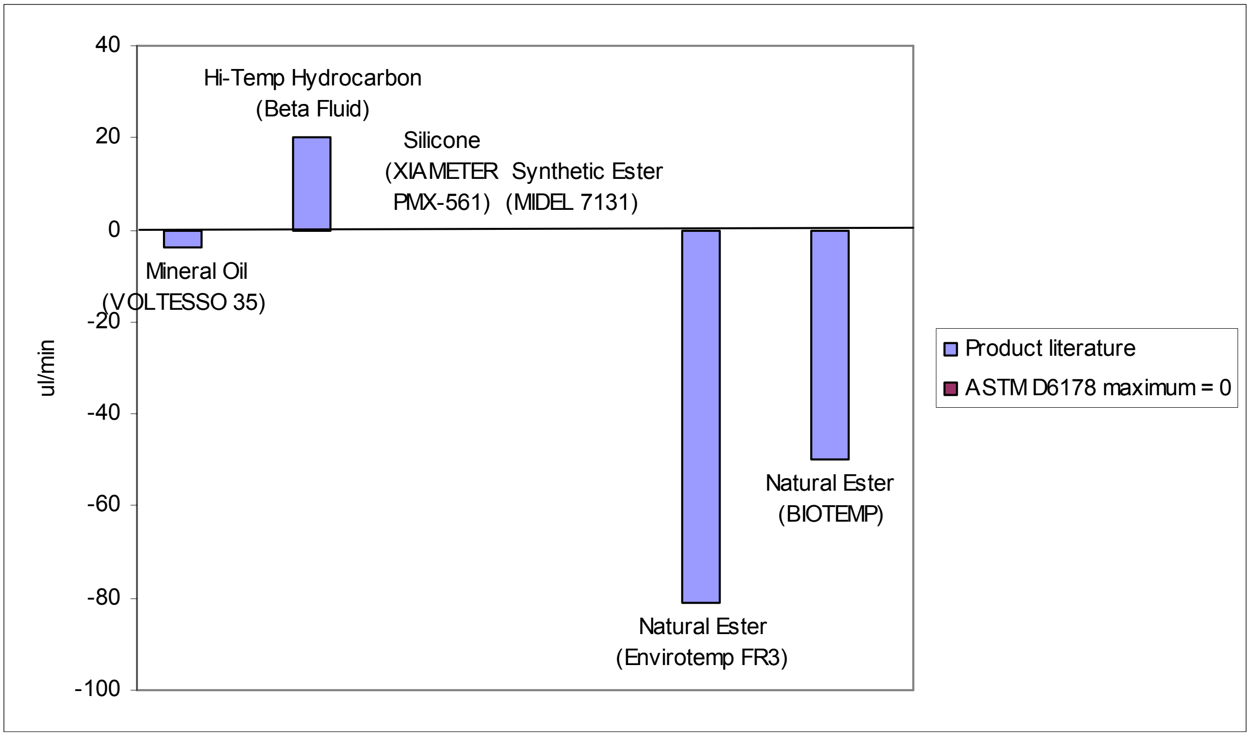

Figure 5-6
Virgin Fluids: Gassing Tendency

ASTM D2300 test results from Appendix D; some values were unavailable
ASTM D6871—*Standard Specification for Natural (Vegetable Oil) Ester Fluids Used in Electrical Apparatus* (Appendix C)

Environmental Technology verification tests of gassing tendency were not conducted for virgin natural ester fluids.

In-Service Natural Ester Fluids

Environmental Technology verification tests of gassing tendency were not conducted for in-service natural ester fluids.

Operational Impacts

Operation and Maintenance

In transformer fluids, a negative gassing tendency is desirable because it minimizes the buildup of hydrogen gas, which can react with oxygen in the presence of a discharge spark to cause equipment explosions. To investigate this possibility, ABB conducted low-energy arc tests of BIOTEMP natural ester fluid and mineral oil. They found that BIOTEMP generated 7 times less gas than mineral oil under the same arcing conditions and concluded that the ‘arc quenching’ effect of BIOTEMP was real. Thus, under transformer operating conditions where discharge sparks occur frequently, operators may choose to retrofill mineral oil-based transformers with natural ester fluids. However, there is no clear, established relationship between gassing tendency measurements and the operating performance of transformers.

CPS claims that standard dissolved gas analyses can be used to signal pending failure of transformers filled with natural ester fluids, since these fluids produce the same fault gases (with standard diagnostic interpretations) as mineral oil.

Recovery and Reuse

Some evidence indicates that reclaiming old, in-service fluids by selectively removing decay products can reduce their gassing tendency (Sabau et al. 2002).

Volume Resistivity

Measured Values

Volume resistivity is a measure of direct current resistance, or the insulating capability of a transformer fluid. High volume resistivity is a desirable fluid property. Standard test method ASTM D1169 is used to test this property.

Virgin Fluids

Values from the product literature for virgin fluids graphed in Figure 5-7 show that VOLTESSO 35 mineral oil has a higher volume resistivity (10^{15} ohm-cm) than the other transformer fluids tested. However, all fluids fall within the desirable range of 10^{13}–10^{16} ohm-cm. The chemical composition of natural ester fluids gives them lower volume resistivity and a higher dissipation factor (see above) than mineral oils. IEEE C57.147 *IEEE Guide for Acceptance and Maintenance of Natural Ester Fluids in Transformers* states that new natural esters have naturally lower volume resistivity than mineral oils.

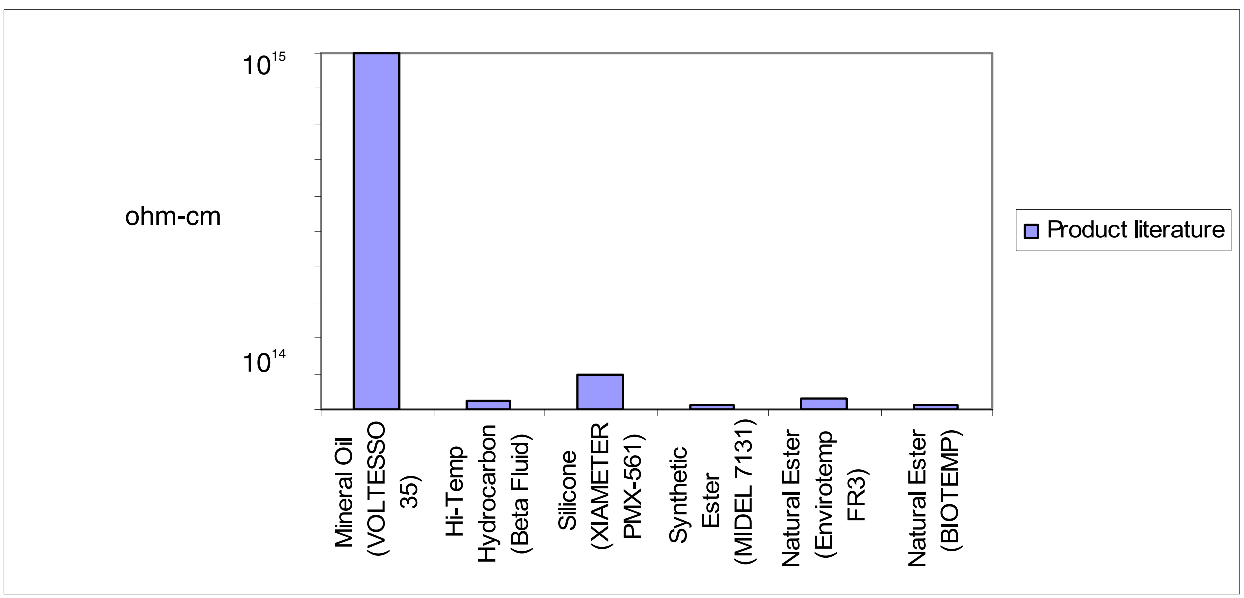

Figure 5-7
Virgin Fluids: Volume Resistivity, 25 °C

ASTM D1169 test results from Appendix D

In-Service Natural Ester Fluids

In Environmental Technology Verification tests of in-service natural ester fluids, researchers used standard method ASTM D4308 to measure electrical conductivity (Figure 5-8), which can be converted to volume resistivity using the relationship 1 pS/m = 1.0 x 10^{14} ohm-cm. BIOTEMP natural ester fluid greatly exceeds the manufacturer minimum for electrical conductivity; Envirotemp FR3 natural ester fluid displays similar electrical conductivity, although no manufacturer minimum is specified. Both fluids have volume resistivity greater than 6.0 x 10^{11} ohm-cm.

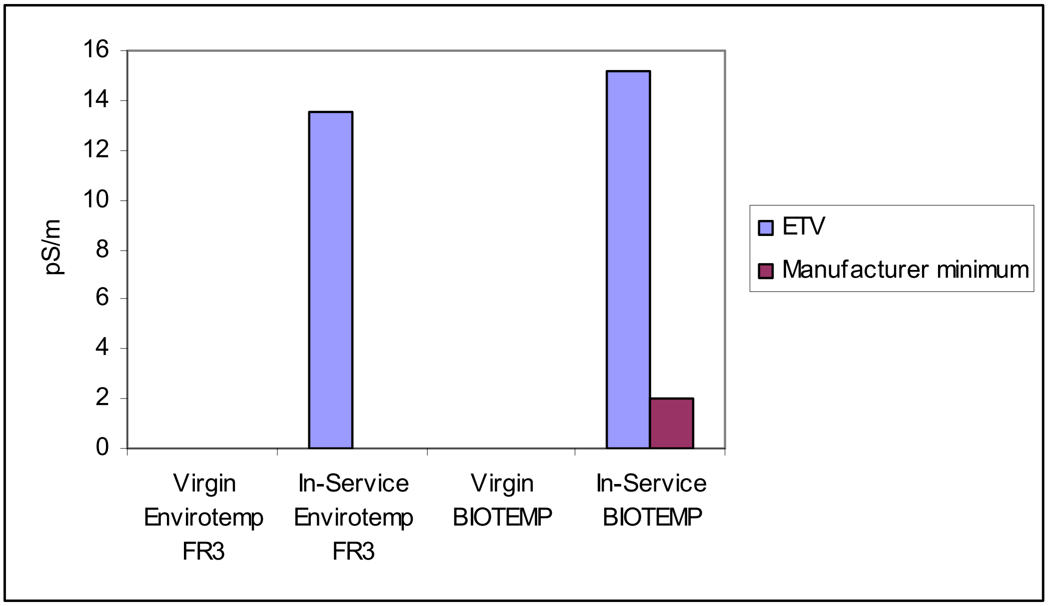

Figure 5-8
In-Service Natural Ester Fluids: Electrical Conductivity, 25 °C

ASTM D4308 test results from Appendix A (Table A-2)
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Operational Impacts

Shipping, Handling, and Storage

High volume resistivity generally indicates a low concentration of conductive contaminants in a transformer fluid. Purchasers should use shipping, handling, and storage procedures that minimize contamination by ion-forming particles.

Operation and Maintenance

ASTM D1169 has not been widely applied to in-service fluids, although lowered resistivity with aging is likely. Electrical conductivity measurements (ASTM D4308) converted to resistivity values show little degradation of natural ester fluids after 2–6 years of service.

Fluid resistivity affects transformer insulation resistance. For example, a transformer filled with mineral oil may have an insulation resistance of 30 meg-ohms. Retrofilling that transformer with a natural ester fluid will lower its insulation resistance to 3 meg-ohms.

Relative Permittivity

Measured Values

Relative permittivity, or the dielectric constant, is a measure of the electrical energy stored in a material. Under ideal conditions, the relative permittivity of a transformer fluid matches the relative permittivity of the cellulose insulation it touches inside a transformer. This match ensures that electrical stress, which is inversely proportional to relative permittivity, is evenly distributed between the fluid (which has lower dielectric strength) and the insulation (which has higher dielectric strength). Standard test method ASTM D924 is used to test this property.

Figure 5-9 displays relative permittivity values from the product literature for virgin transformer fluids. According to these data, MIDEL 7131 synthetic ester fluid and the natural ester fluids (Envirotemp FR3 and BIOTEMP) have higher relative permittivity (3.2 K) than VOLTESSO 35 mineral oil (2.2 K). This observation accords with IEEE C57.147 *IEEE Guide for Acceptance and Maintenance of Natural Ester Fluids in Transformers*, which states that new natural esters have naturally higher relative permittivity than mineral oil, closer to that of cellulose insulation. Cellulose, or impregnated paper, insulation typically has a relative permittivity of 3.1–4.8 K. Note that XIAMETER PMX-561 silicone fluid (2.7 K) also provides a good relative permittivity match to cellulose insulation.

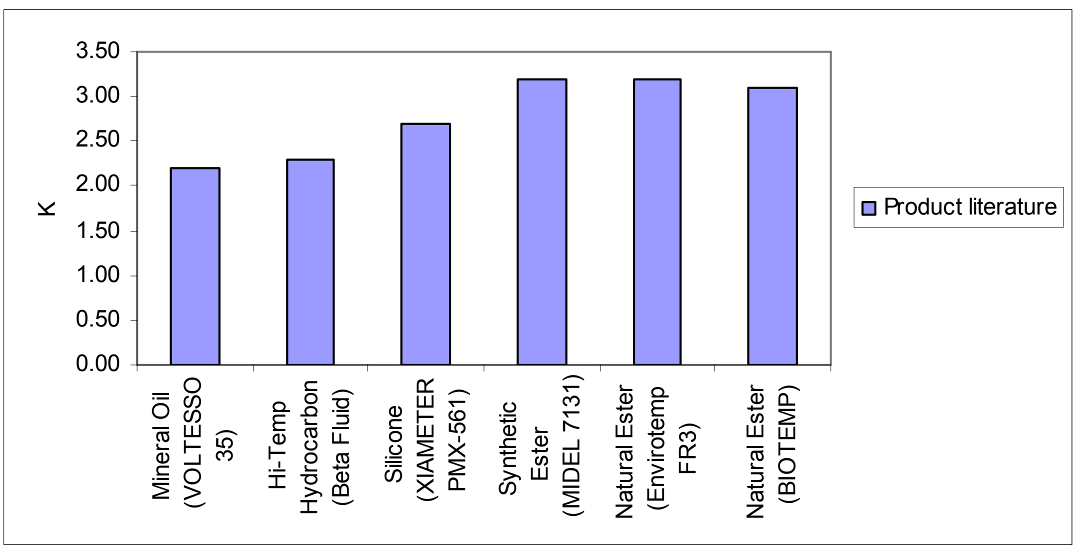

Figure 5-9
Virgin Fluids: Relative Permittivity (Dielectric Constant), 25 °C

ASTM D924 test results from Appendix D

ASTM D6871 *Standard Specification for Natural (Vegetable Oil) Ester Fluids Used in*

Electrical Apparatus standard suggests 3.2 K as a typical relative permittivity value for natural ester fluids; this is not a mandatory standard.

Environmental Technology Verification tests of relative permittivity were not conducted for virgin natural ester fluids.

In-Service Natural Ester Fluids

Environmental Technology Verification tests of relative permittivity were not conducted for in-service natural ester fluids.

6
CHEMICAL PROPERTIES OF TRANSFORMER FLUIDS AND THEIR OPERATIONAL IMPACTS

This section compares transformer fluid performance on an array of chemical properties including water content, oxidation stability and neutralization number, interfacial tension, corrosive sulfur, and PCBs.

Water Content

Measured Values

Standard test method ASTM D1533 is used to estimate the total water content of transformer fluids. The dielectric strength of a fluid starts to fall when its water content reaches 50% saturation. The absolute amount of water needed to reach a particular percentage of saturation varies by fluid type. For example, 50% saturation at room temperature is 30–35 ppm for mineral oil, but 500–600 ppm for synthetic and natural ester fluids. Saturation point increases with temperature.

Virgin Fluids

Figure 6-1 displays the water content of virgin transformer fluids received in a tanker and tested at room temperature (20 ºC). As expected, MIDEL 7131 synthetic ester fluid and BIOTEMP natural ester fluid contain more water than VOLTESSO 35 mineral oil or Beta Fluid high-temperature hydrocarbon fluid. According to product literature, the water content of XIAMETER PMX-561 silicone fluid falls between values for these two groups.

In Environmental Technology Verification tests, both Envirotemp FR3 and BIOTEMP natural ester fluids meet their manufacturer's specifications for moisture content, and fall well below the ASTM D6871 *Standard Specification for Natural (Vegetable Oil) Ester Fluids Used in Electrical Apparatus* maximum value for fluids of this type.

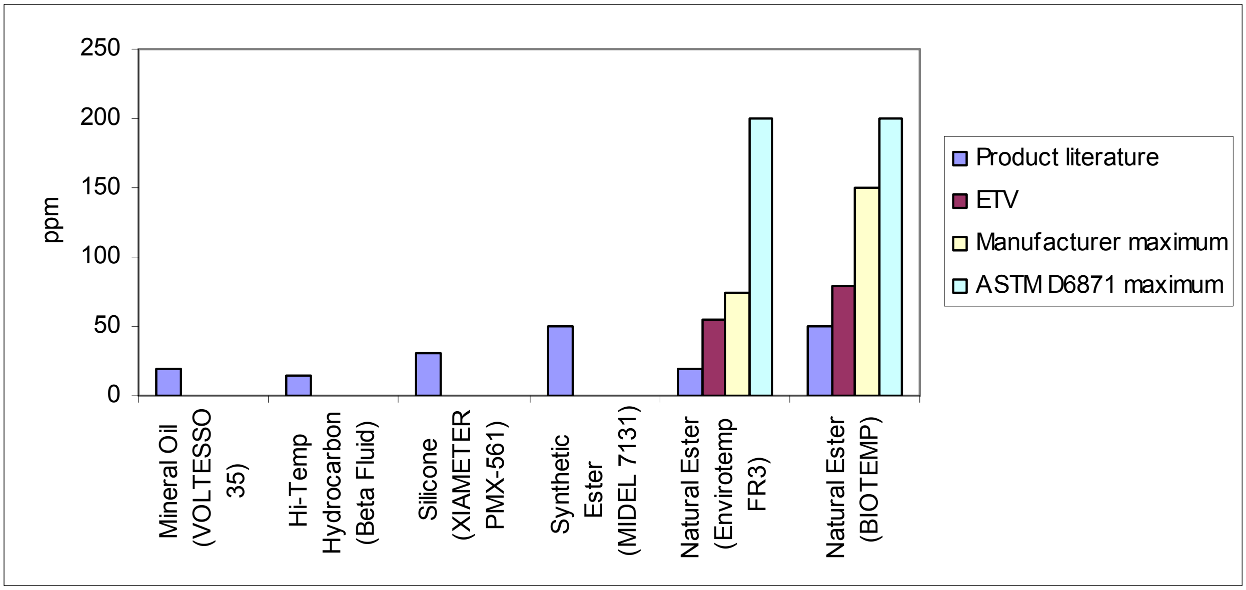

Figure 6-1
Virgin Fluids: Water Content, 20 ºC (bulk tanker)

ASTM D1533 test results from Appendix A (Table A-2) and Appendix D

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ASTM D6871—*Standard Specification for Natural (Vegetable Oil) Ester Fluids Used in Electrical Apparatus* (Appendix C)

Note that synthetic ester water content is determined by standard method IEC 60814, an international test method commonly used in Europe where MIDEL 7131 is largely employed; IEC and ASTM standard methods may differ.

In-Service Natural Ester Fluids

In Environmental Technology Verification tests (Figure 6-2), both Envirotemp FR3 and BIOTEMP natural ester fluids meet their manufacturers' specifications for maximum water content of in-service fluids. In-service (up to 4.8 years) and virgin Envirotemp FR3 samples have the same water content. Surprisingly, in-service (up to 2.5 years) BIOTEMP contains less water than virgin BIOTEMP. With respect to water content, IEEE C57.147 *IEEE Guide for Acceptance and Maintenance of Natural Ester Fluids in Transformers* states that the recommended limit is application- and user-specific for in-service natural ester fluids.

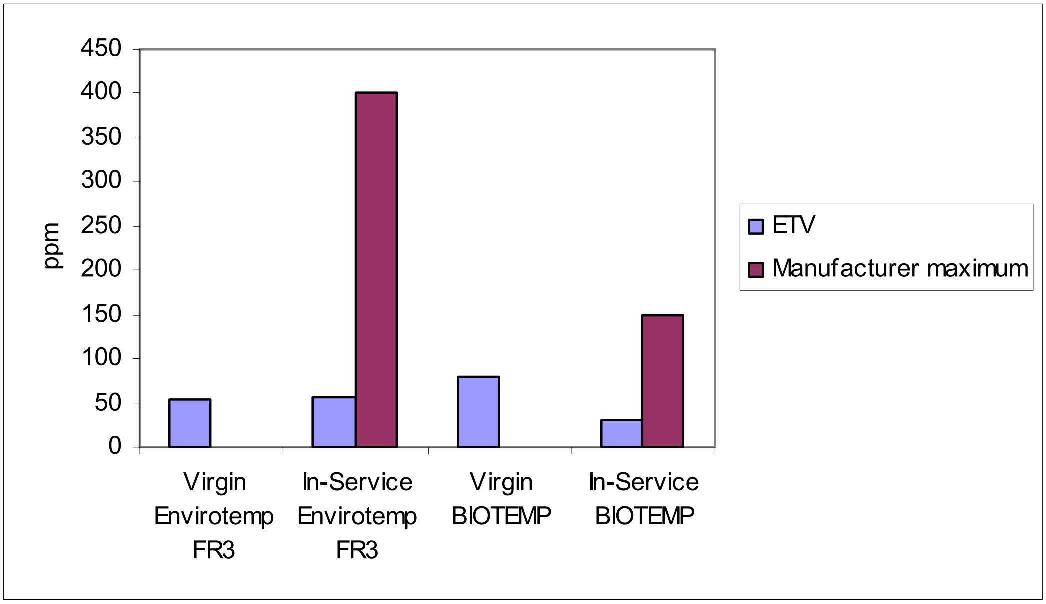


Figure 6-2
In-Service and Virgin Natural Ester Fluids: Water Content, 20 °C

ASTM D1533 test results from Appendix A (Table A-2)
ETV—Environmental Technology Verification

Operational Impacts

Shipping, Handling, and Storage

During shipping, handling, and storage, it is important to protect transformer fluids from exposure to moisture in the air. If virgin fluids have adsorbed excess water, it must be removed to acceptable limits before the fluids can be placed into service. This is accomplished by filtering or subjecting fluids to vacuum dehydration, which removes both excess water and gas. Care must be taken not to remove pour point depressants or antioxidant additives.

In general, natural ester fluids are stored, handled, filtered, and degassed in the same way as mineral oil. However, because they are hygroscopic, these fluids draw contaminating moisture from the air at a much faster rate than mineral oil.

Operation and Maintenance

Water content increases as transformer fluids age. Values above certain limits may indicate pending failure of fluid dielectric strength. Table 6-1 displays provisional water content values that should trigger prompt additional investigation of in-service natural ester fluids, according to IEEE C57.147 *IEEE Guide for Acceptance and Maintenance of Natural Ester Fluids in Transformers.*

Table 6-1
Service-Aged Natural Ester Fluids: Provisional Water Content Triggering Prompt Investigation

Transformer Voltage Class	ASTM D1533, ppm
≤ 69 kV	400 minimum
> 69 kV < 230 kV	400 minimum
230 kV and above	400 minimum

Studies conducted by fluid manufacturers suggest that insulating paper wrapped around transformer coils ages at a slower rate when bathed in ester-based fluids than when bathed in mineral oil. It is unknown whether aging slows because the hygroscopic ester-based fluids draw moisture out of the paper until saturation equilibrium is reached (protecting the paper from deterioration due to cellulose hydrolysis), or because these fluids react chemically with cellulose to stabilize the paper at high temperatures typical of transformer operation.

Regardless of mechanism, ester-based fluids apparently prolong the life of insulating paper and hence, of transformers themselves. To challenge its longevity, researchers subject insulating paper to thermal stress that accelerates aging. After performing full-scale accelerated aging (thermal cycling) tests on insulating paper in transformers filled with natural ester fluids, CPS found that Envirotemp FR3 "extends insulation life by a factor of as much as 5–8 times . . ." (McShane 2009) compared with mineral oil. Envirotemp FR3-filled transformers in these studies remained in service 4 times longer than those filled with mineral oil. Further observations indicate that insulating paper impregnated with natural ester fluids can operate at higher "hotspot" temperatures than insulating paper impregnated with mineral oil. This increases the overload capacity of natural ester fluid-filled transformers. These outcomes make ester-based fluids a good choice for companies seeking to delay transformer replacement and to lower life-cycle costs.

Some have proposed adding natural ester fluids to mineral-oil filled transformers to create blends that slow the insulating paper aging process. Although this retrofill strategy has successfully removed moisture from insulating paper in the field, the appropriate blend ratios and impacts on other physical, dielectric, and chemical properties of the fluids involved are site-specific. Retrofills that completely replace mineral oil with natural ester fluid may remove moisture buildup and prolong insulating paper life while avoiding the problems posed by fluid blends.

Recovery and Reuse

Ideally, used transformer fluids can be reconditioned to extend their service life, avoid disposal and liability issues, and reduce overall costs. One objective of reconditioning is to remove water from used fluids. IEEE C57.147 *IEEE Guide for Acceptance and Maintenance of Natural Ester Fluids in Transformers* defines reconditioning as "the removal of water and solid materials by mechanical means," and lists several types of filters, centrifuges, and vacuum dehydrators that are effective for this purpose.

Dow Corning describes commercially available systems that combine vacuum distillation with fine particle filtration to recondition XIAMETER PMX-561 silicone fluid in transformers operating on line. Dow Corning also offers its customers a buy-back program that recycles used silicone fluid as feedstock for other products. Such buy-back programs are also well-established for mineral oil, but remain uncertain for natural ester fluids.

Oxidation Stability and Neutralization Number

Measured Values

The oxidation stability of transformer fluids is compromised by the formation of sludge and acid products. Fluids with good oxidation stability maximize service life by reducing the formation of these constituents, which can increase electrical conduction and decrease heat transfer.

Standard test method ASTM D2440 measures the formation of sludge and acid products—indicated by higher neutralization (acid) numbers—under specific test conditions. These test conditions are suitable for evaluating the overall consistency of oxidation stability for fluids and the performance of oxidation inhibitors added to the fluids. However, the test conditions do not model the whole insulation system (fluid, paper, enamel, wire) and thus give results that cannot predict performance in the field.

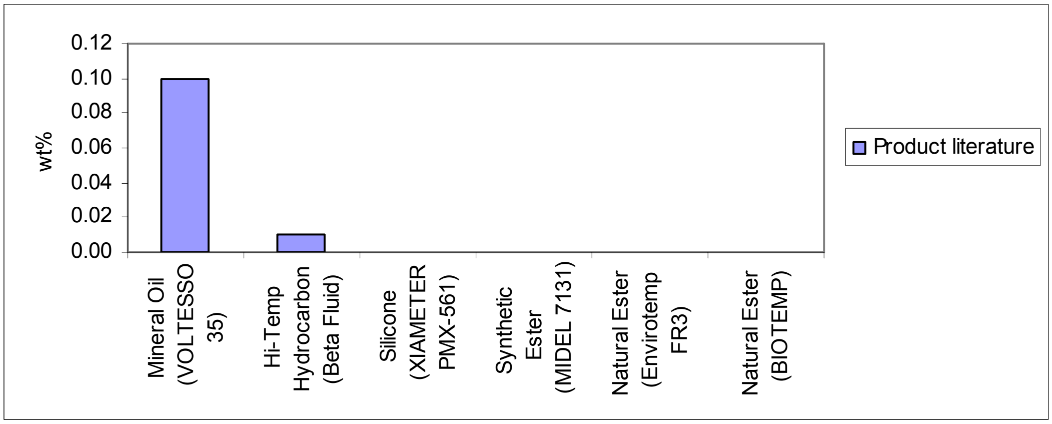
ASTM D2440 was developed to evaluate the oxidation stability of virgin mineral oils. ASTM D6871 *Standard Specification for Natural (Vegetable Oil) Ester Fluids Used in Electrical Apparatus* states that the "oxidation stability requirement and appropriate test method for natural ester insulating fluids have not been established." This is so because mineral oil and natural ester fluids have different mechanisms of oxidation. When mineral oil oxidizes, it forms insoluble sludge that precipitates out of solution to coat the internal surfaces of a transformer. When natural ester fluids oxidize, they form large molecules (oligomers) that remain in solution, increasing fluid viscosity. Both forms of oxidation eventually cause a transformer to overheat, but only mineral oil oxidation adversely affects fluid dielectric strength.

IEEE C57.147 *IEEE Guide for Acceptance and Maintenance of Natural Ester Fluids in Transformers* notes that ASTM D2440 is unsuitable for testing vegetable oils. It describes alternative oxidation stability tests for natural ester fluids developed by Doble Engineering Company (Watertown, MA). These tests are applicable to natural ester fluids in realistic operating environments. Doble's sludge-free life (SFL) test evaluates time to sludge formation in fluid samples taken at 8-hour intervals. Doble's power factor valued oxidation (PFVO) test records power factor measurements over time as the fluid oxidizes while exposed to air and a copper catalyst at 95 ºC.

Given the difficulties in measuring the oxidation stability of natural ester fluids, it is useful that standard test method ASTM D974 is available. This method measures transformer fluid degradation products and expresses the result as an acid or base number, depending on product chemistry. ASTM D974 is suitable for use with virgin and in-service fluids. IEEE C57.147 *IEEE Guide for Acceptance and Maintenance of Natural Ester Fluids in Transformers* recognizes this method and ASTM D6871 *Standard Specification for Natural (Vegetable Oil) Ester Fluids Used in Electrical Apparatus* lists a maximum neutralization number based on its use.

Virgin Fluids

Figures 6-3 and 6-4 describe the oxidation stability of VOLTESSO 35 mineral oil and Beta Fluid high-temperature hydrocarbon fluid, as measured by ASTM D2440 and reported in the product literature. Before current practice deemed ASTM D2440 unsuitable for testing vegetable oils, researchers used the method in Environmental Technology Verification tests of BIOTEMP natural ester fluid and Envirotemp FR3 natural ester fluid (where the product gelled during testing). Results of these Environmental Technology Verification tests are not reported here.



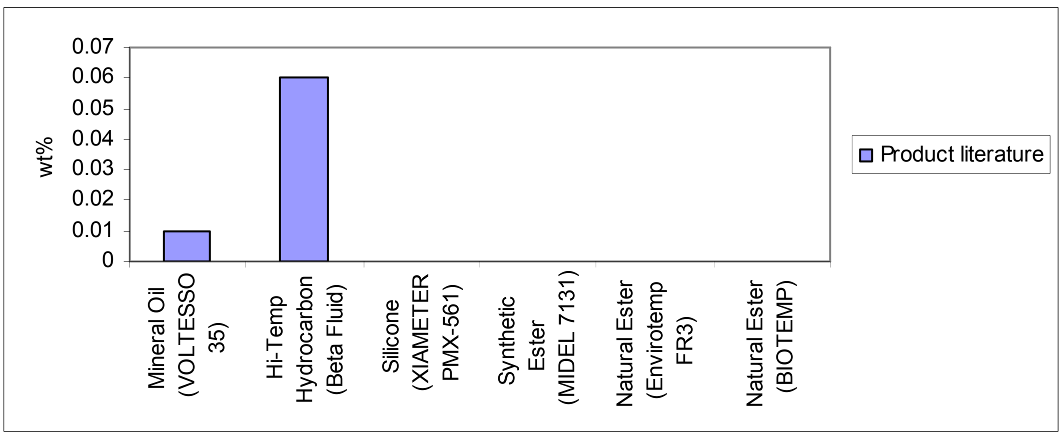
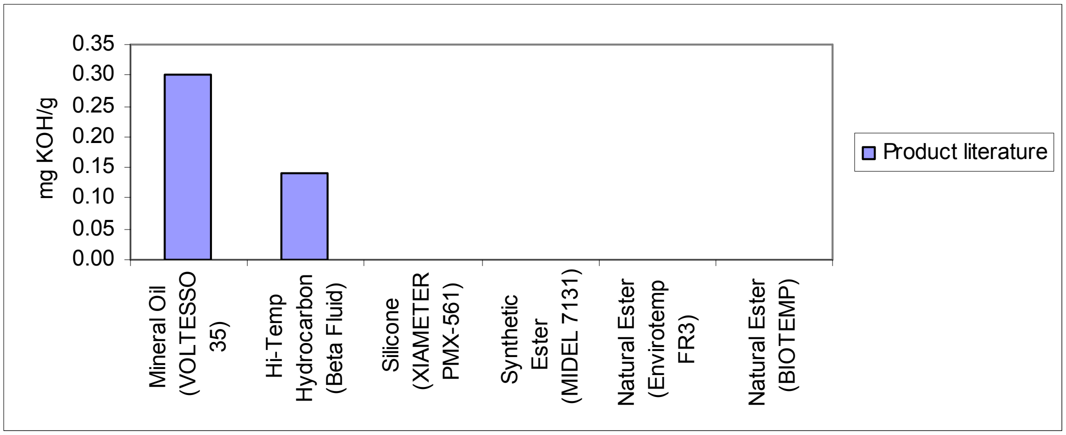


Figure 6-3
Virgin Fluids: Oxidation Stability—Sludge, (top) 72 h, 100 °C and (bottom) 164 h, 110 °C

ASTM D2440 test results from Appendix D; some values were unavailable

A pattern emerges in the figures. After 72 hours, VOLTESSO 35 mineral oil has more sludge and a higher neutralization number than Beta Fluid high-temperature hydrocarbon fluid. After 164 hours, the reverse is true. Thus, Beta Fluid may have less oxidation stability over time. These results support the hypothesis that mineral oil degradation products are more soluble in oil than high-temperature hydrocarbon degradation products, making mineral oil less susceptible to sludge and deposit formation.



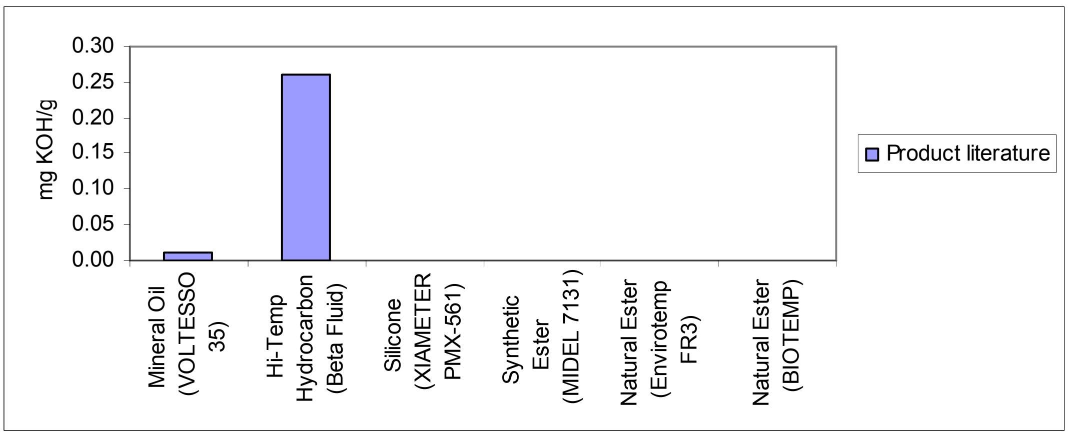


Figure 6-4
Virgin Fluids: Oxidation Stability—Neutralization Number, (top) 72 h, 100 °C and (bottom) 164 h, 110 °C

ASTM D2440 test results from Appendix D; some values were unavailable

Figure 6-5 displays the results of ASTM D974 neutralization number testing for virgin fluids. It is clear that MIDEL 7131 synthetic ester fluid and the two natural ester fluids have higher neutralization numbers than VOLTESSO 35 mineral oil and XIAMETER PMX-561 silicone fluid. This result indicates that ester-based fluids are somewhat more likely to form acid degradation products than mineral oil or silicone fluids. It supports the IEEE C57.147 *IEEE Guide for Acceptance and Maintenance of Natural Ester Fluids in Transformers* statement that natural ester fluids have naturally higher acid numbers than hydrocarbon-based fluids, even when new. The addition of oxidation inhibitors helps to alleviate this problem

In Environmental Technology Verification tests, virgin Envirotemp FR3 natural ester fluid meets limits set by its manufacturer and by ASTM D6871 *Standard Specification for Natural (Vegetable Oil) Ester Fluids Used in Electrical Apparatus*. Environmental Technology Verification tests of virgin BIOTEMP natural ester fluid employing ASTM D974 were not performed.

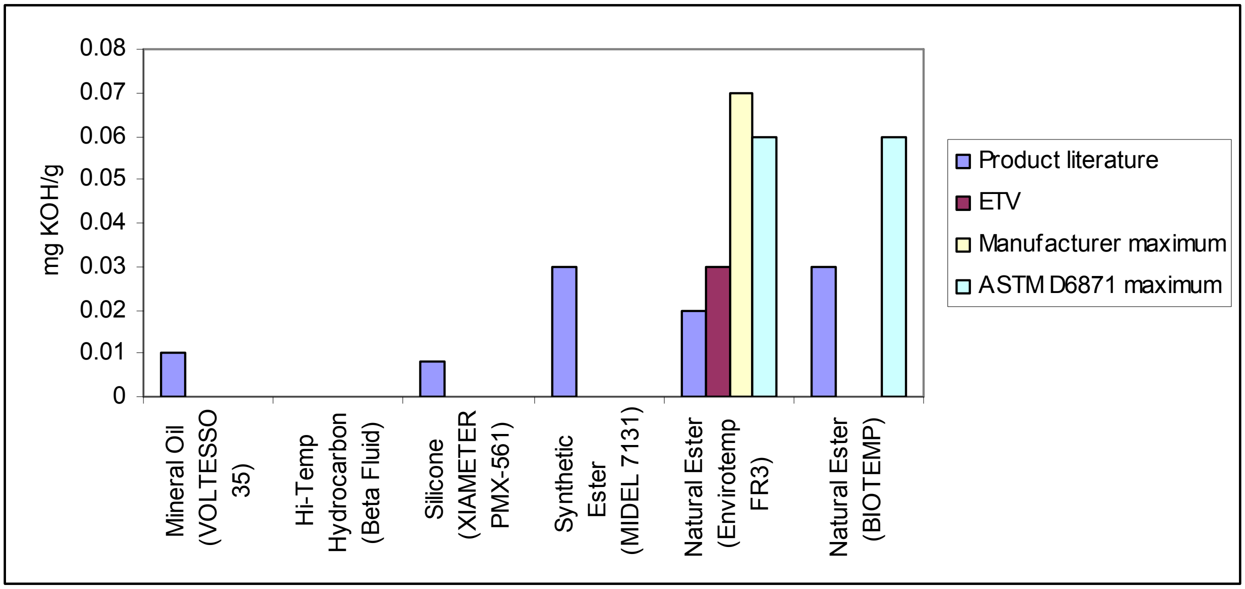


Figure 6-5
Virgin Fluids: Neutralization Number

ASTM D974 test results from Appendix A (Table A-2) and Appendix D; some values were unavailable

ETV—Environmental Technology Verification

ASTM D6871—*Standard Specification for Natural (Vegetable Oil) Ester Fluids Used in Electrical Apparatus* (Appendix C)

In-Service Natural Ester Fluids

Environmental Technology Verification tests of in-service Envirotemp FR3 natural ester fluid show that its neutralization number remains well below the manufacturer's specified maximum (Figure 6-6). It is also clear that in-service fluids (up to 4.8 years of use) hardly differ from virgin fluids tested with ASTM D974. Again, ASTM D974 tests of in-service BIOTEMP natural ester fluid were not performed.

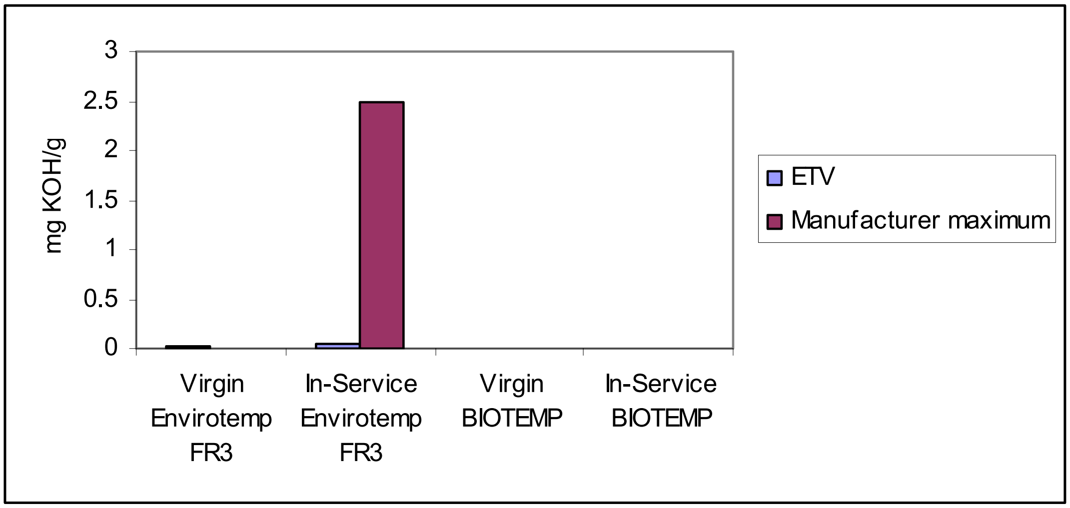


Figure 6-6
In-Service and Virgin Natural Ester Fluids: Neutralization Number

ASTM D974 test results from Appendix A (Table A-2)
ETV—Environmental Technology Verification

Operational Impacts

Shipping, Handling, and Storage

To prevent oxidation, fluids should be stored in sealed containers without exposure to air and moisture, away from strong oxidizing agents. Since natural ester fluids are more susceptible to oxidation than mineral oil, extra care must be taken in their handling and storage. For example, when these fluids are exposed to air, oxidation occurs only at their surface. Thus, IEEE C57.147 *IEEE Guide for Acceptance and Maintenance of Natural Ester Fluids in Transformers* recommends that users minimize air and heat exposure for surfaces with thin films of fluid, such as hoses, fittings, and core and coils removed from the tank.

One company responding to EPRI's 2009 survey noted the following cautions when using Envirotemp FR3:

- For long-term storage, the fluid must be placed in a dry, well ventilated and heated building with minimal exposure to open air and moisture to ensure that the fluid maintains its insulating properties.
- The fluid polymerizes if there is a surface area in direct contact with open air and sunlight. Sunlight may affect its color.
- Envirotemp FR3 may oxidize on prolonged contact with painted surfaces. One company facility had to repaint a vehicle when fluid accidentally spilled on its body.

Installation

Because of their susceptibility to oxidation, natural ester fluids are unsuitable for use in transformers with free breathing conservator designs.

Operation and Maintenance

Neutralization (acid) number increases as transformer fluids age. Values above certain limits indicate that a transformer containing the fluid may overheat. Table 6-2 displays provisional neutralization numbers that should trigger prompt additional investigation of in-service natural ester fluids, according to IEEE C57.147 *IEEE Guide for Acceptance and Maintenance of Natural Ester Fluids in Transformers.*

Table 6-2
Service-Aged Natural Ester Fluids: Provisional Neutralization (Acid) Numbers Triggering Prompt Investigation

Transformer Voltage Class	ASTM D974, mg KOH/g
≤ 69 kV	0.3 minimum
> 69 kV < 230 kV	0.3 minimum
230 kV and above	0.3 minimum

To preserve the life of BIOTEMP natural ester fluid if exposure to air exceeds 5 hours, ABB recommends degassing and refilling the transformer headspace with dry nitrogen.

Recovery and Reuse

IEEE C57.147 *IEEE Guide for Acceptance and Maintenance of Natural Ester Fluids in Transformers* defines reclaiming as "the removal of acidic and colloidal contaminants and oxidized matter by chemical and adsorbent means." Most reclamation processes involve the use of Fuller's earth. Users should consult the fluid manufacturer for recommended procedures. Consultation is especially important since reclamation may remove additives—which will need to be restored—and well as contaminants.

Cleanup

Natural ester fluid spills should be cleaned up promptly. Films of these fluids exposed to air oxidize quickly, turning sticky to the touch after about a week and polymerizing to a solid after several months. Thus, fresh spill cleanup is easy but old spill cleanup is difficult.

Interfacial Tension

Measured Values

When transformer fluids deteriorate, they may form small amounts of soluble polar contaminants (such as inorganic acids, bases, and salts), as well as oxidation products. Standard test method ASTM D971 detects these contaminants, which decrease the interfacial tension between transformer fluids and water. The higher the test value, the fewer contaminants in the fluid.

Virgin Fluids

The interfacial tension of virgin Envirotemp FR3 and BIOTEMP natural ester fluids is inherently lower than that of virgin VOLTESSO 35 mineral oil (Figure 6-7). This is due mainly to differences in chemistry, including higher water adsorption by the natural ester fluids.

In Environmental Technology Verification tests, Envirotemp FR3 natural ester fluid exceeds the manufacturer's performance specifications for interfacial tension with a result similar to that advertised in its product literature. ASTM has not published an interfacial tension acceptance limit for virgin natural ester fluids, so no ASTM D6871 *Standard Specification for Natural (Vegetable Oil) Ester Fluids Used in Electrical Apparatus* limit appears on the graph.

Environmental Technology Verification tests of interfacial tension were not conducted for BIOTEMP virgin natural ester fluids.

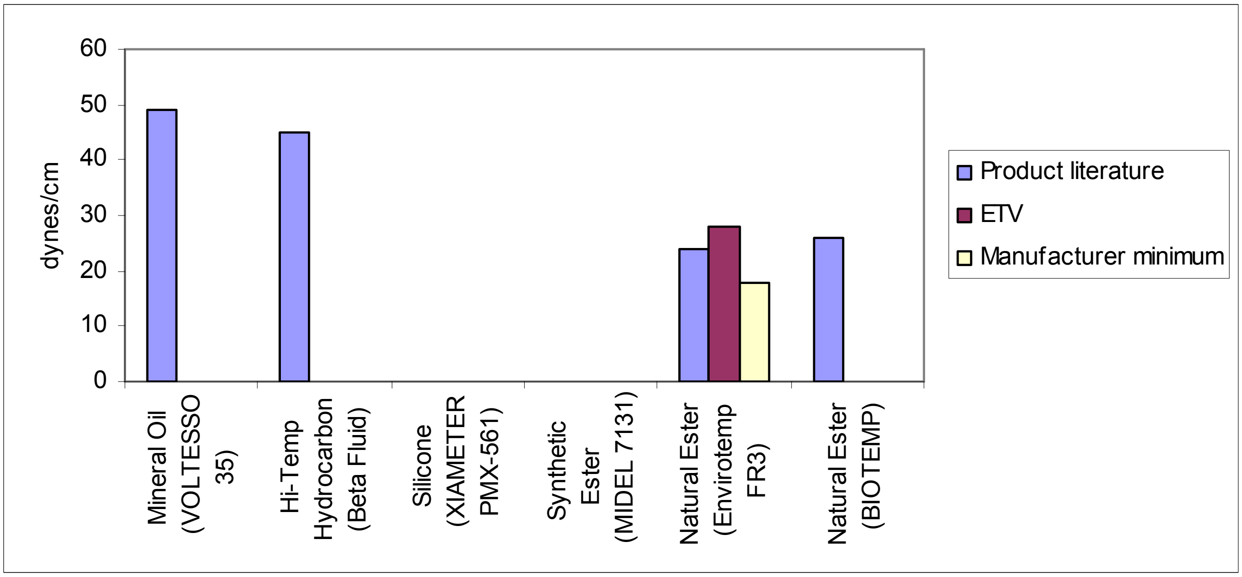


Figure 6-7
Virgin Fluids: Interfacial Tension, 25 °C

ASTM D971 test results from Appendix A (Table A-2) and Appendix D; some values were unavailable
ETV—Environmental Technology Verification

In-Service Natural Ester Fluids

Figure 6-8 compares interfacial tension values from Environmental Technology Verification tests for virgin and in-service Envirotemp FR3 natural ester fluids. As expected, the in-service sample has lower interfacial tension, indicating the presence of some polar contaminants. However, Envirotemp FR3 still exceeds its manufacturer's performance standard for in-service fluid.

Environmental Technology Verification tests of interfacial tension were not conducted for BIOTEMP in-service natural ester fluids.

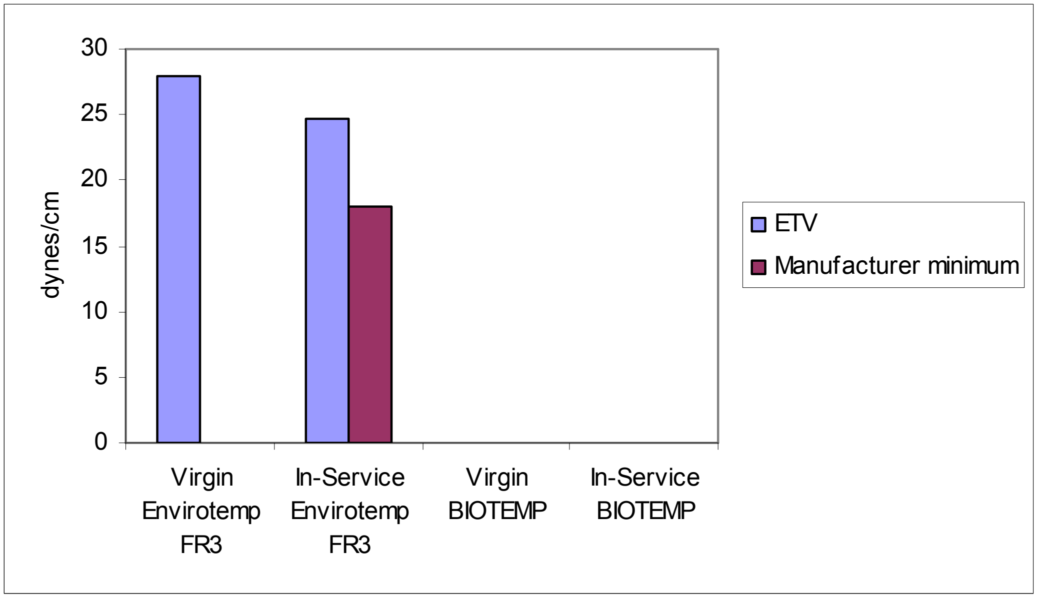


Figure 6-8
In-Service and Virgin Natural Ester Fluids: Interfacial Tension, 25 °C

ASTM D971 test results from Appendix A (Table A-2)
ETV—Environmental Technology Verification

Operational Impacts

Operation and Maintenance

The diagnostic significance of interfacial tension for service-aged natural ester fluids is unclear, since these fluids have naturally lower interfacial tension than mineral oil. IEEE C57.147 *IEEE Guide for Acceptance and Maintenance of Natural Ester Fluids in Transformers* suggests that a 40% drop from virgin fluid values should trigger further investigation. IEEE requires additional field data before establishing interfacial tension limits for service-aged natural ester fluids.

Corrosive Sulfur

Measured Values

Sulfur compounds present in transformer fluids can corrode metals. Transformer operating temperature and the duration of metal exposure to these compounds determines the extent of corrosion. For example, corrosion due to constant contact between a contaminated fluid and the transformer coil may cause premature coil failure.

Standard test method ASTM D1275B is a visual test indicating the presence of corrosive sulfur in transformer fluids.

Virgin Fluids

Although corrosive sulfur compounds occur naturally in petroleum-based transformer fluids, refining and treatment can reduce them to negligible levels. According to IEEE C57.147 *IEEE Guide for Acceptance and Maintenance of Natural Ester Fluids in Transformers*, these fluids do not contain corrosive sulfur compounds.

The following virgin transformer fluids had no detectable corrosive sulfur compounds in ASTM D1275B testing:

- VOLTESSO 35 mineral oil
- Beta Fluid high-temperature hydrocarbon fluid
- MIDEL 7131 synthetic ester fluid
- Envirotemp FR3 natural ester fluid
- BIOTEMP natural ester fluid

Data were unavailable for XIAMETER PMX-561 silicone fluid.

Environmental Technology Verification tests of corrosive sulfur were not conducted for virgin natural ester fluids.

In-Service Natural Ester Fluids

Environmental Technology Verification tests of corrosive sulfur were not conducted for in-service natural ester fluids.

Operational Impacts

Operation and Maintenance

Since natural ester fluids do not contain corrosive sulfur, ABB's claim that BIOTEMP is noncorrosive at temperatures well above those of normal operation is reasonable. However, one company responding to EPRI's 2009 survey complained that Envirotemp FR3 corrodes the gaskets in transformers, increasing maintenance costs. The mechanism of corrosion is in this case is unclear.

Recently, EPRI attributed the failure of several large, relatively new power transformers to corrosive sulfur contamination in transformer fluids (McShane 2006). Researchers hypothesized that thermally unstable sulfur-bearing compounds in virgin fluids pass standard tests, but then convert to corrosive sulfur in transformers operating under heavy load at high temperatures. No particular fluid type or manufacturer was implicated in the failures.

Polychlorinated Biphenyls (PCBs)

Measured Values

Polychlorinated biphenyls (PCBs) are persistent, bioaccumulative toxins banned from U.S. production in 1976. Askarels are PCB-containing mixtures formerly used as transformer fluids. Current practice requires transformer fluids to be PCB-free.

Standard test method ASTM D4059 uses gas chromatography to determine the concentration of PCBs in transformer fluids. The precision and bias of this test method has been established only for mineral oils and silicone fluids.

Virgin Fluids

In ASTM D4059 testing, PCB concentrations were nondetectable in XIAMETER PMX-561 silicone fluid and BIOTEMP natural ester fluid. Beta Fluid high-temperature hydrocarbon fluid had less than 2 ppm PCBs. Imperial Oil claims that VOLTESSO 35 mineral oil contains no PBCs, but ASTM D4059 data were unavailable. Data were likewise unavailable for MIDEL 3171 synthetic ester fluid, and Envirotemp FR3 natural ester fluid.

According to IEEE C57.147 *IEEE Guide for Acceptance and Maintenance of Natural Ester Fluids in Transformers*, these fluids do not contain PCBs.

Environmental Technology Verification tests of PCBs were not conducted for virgin natural ester fluids.

In-Service Natural Ester Fluids

Environmental Technology Verification tests of PCBs were not conducted for in-service natural ester fluids.

Operational Impacts

Shipping, Handling, and Storage

The federal Toxic Substances Control Act (40CFR761.1) regulates handling of transformer fluids containing PCBs and DOT regulations apply to shipping them. The PCB concentration of the fluid determines the procedures required.

Operation and Maintenance

Personnel should take extra precautions to prevent leaks and spills from transformers filled with fluid blends created by “topping off” or retrofilling with environmentally acceptable fluids. If transformers were previously filled with Askarel, these fluid blends may contain PBCs that should not be released to the environment.

Recovery and Reuse

Some fat rendering operations are reluctant to accept recycled Envirotemp FR3 natural ester fluid, according to one company responding to EPRI’s 2009 survey. Evidently, fat renderers wrongly assume that the fluid must contain PCBs since it is associated with transformers.

Disposal

Although virgin transformer fluids may not contain PCBs, spent fluids can be contaminated by use in transformers formerly filled with Askarels. Companies should test spent fluids for PCB content before disposal. Disposal costs are higher when dealing with hazardous waste.

Cleanup

The presence of PCBs in fluid spills will trigger costly, hazardous waste cleanup requirements.

7
ENVIRONMENTAL PROPERTIES OF TRANSFORMER FLUIDS AND THEIR OPERATIONAL IMPACTS

This section discusses transformer fluid toxicity and hazardous waste classification, biodegradability, and transport and fate in the environment.

Toxicity and Hazardous Waste Classification

The discussion begins with aquatic toxicity, one potential indicator that a fluid may be classified as hazardous. It expands to include toxicity in the workplace, where personnel are exposed to transformer fluids, and includes a review of the hazardous waste classification as it applies to natural ester transformer fluids.

Measured Values

Aquatic toxicity describes the health impact of transformer fluids on fish and other aquatic organisms when the fluids are released to waterways. Bioassays are used to measure aquatic toxicity. In a typical fish acute bioassay, lethal concentration 50 (LC_{50}) indicates the fluid concentration in water having a 50% chance of killing the fish.

Two 96-hour fish acute bioassays are discussed in this report. They are:

1. Test procedures described in *Methods for Measuring the Acute Toxicity of Effluents and Receiving Waters to Freshwater and Marine Organisms* (EPA 1993).
    - Environmental Technology Verification studies used this bioassay to test Envirotemp FR3 natural ester fluid on juvenile and adult fathead minnows, and to test BIOTEMP natural ester fluid on juvenile fathead minnows. In both cases, personnel prepared the samples by agitating them for 6 hours in a wrist-action shaker. This dissolved the samples in 200 ml of water before they were added to the bioassay fish tank. This sample preparation method, called "Static Acute Bioassay Procedures for Hazardous Waste Samples," was developed by the California Department of Fish and Game, Water Pollution Control Laboratory, and is specified in the Code of California Regulations, Title 22, Section 66261.24(a)(6). It specifically targets the samples' potential to become hazardous spent waste.
    - Parametrix, an independent laboratory contracted by ABB, used the EPA bioassay to test BIOTEMP on juvenile rainbow trout. They prepared the samples by using an acetone carrier solvent to make the fluid miscible in water. This is the sample preparation procedure described in the EPA method.
2. Organization of Economic Cooperation and Development (OECD) Test Guideline (TG) 203, "Fish Acute Toxicity Test" (OECD 2008).
    - Global Tox, an independent laboratory contracted by CPS, used this bioassay to test Envirotemp FR3 on juvenile rainbow trout. They prepared the samples by using an acetone carrier solvent.

Virgin Fluids

Figure 7-1 presents the results of fish bioassays for acute aquatic toxicity of Envirotemp FR3 and BIOTEMP virgin natural ester transformer fluids. These bioassays were conducted in Environmental Technology Verification tests and in tests performed by independent laboratories under contract to fluid manufacturers (historic data). According to the California Toxicity Criterion (Code of California Regulations, Title 22, Section 66261.24(a)(6)), virgin fluids with LC_{50} less than 500 mg/l (measured in soft water) are considered to be toxic. All of the bioassay values obtained in Environmental Technology Verifications tests of the natural ester fluids fall in the toxic range (below 500 mg/l). In contrast, historic data from fluid manufacturers show bioassay values well outside the toxic range (above 500 mg/l).

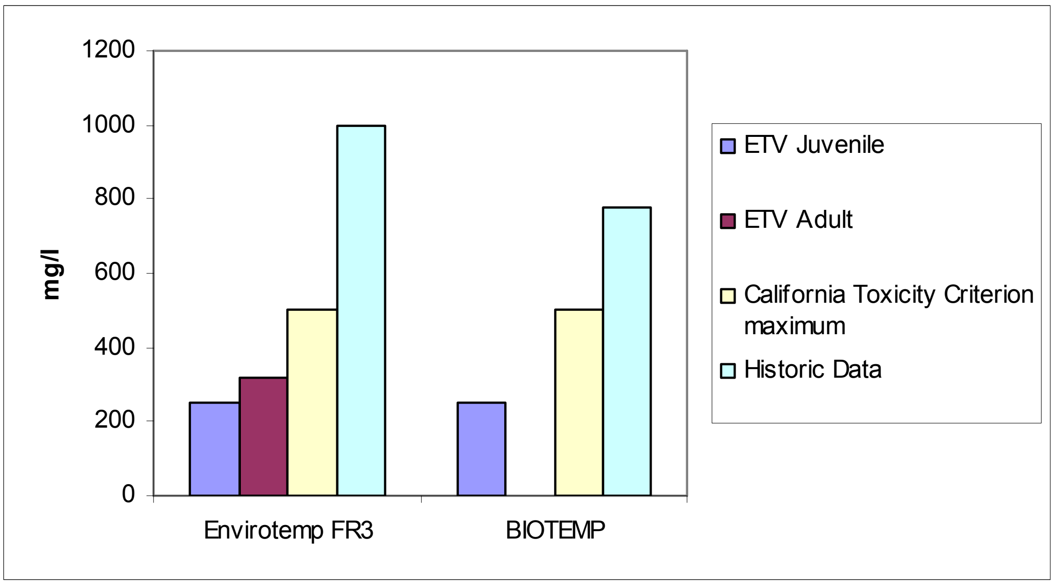


Figure 7-1
Virgin Natural Ester Fluids: Aquatic Toxicity

Fish bioassay results from Appendix E; some values were unavailable

ETV—Environmental Technology Verification

California Toxicity Criterion—virgin fluids with LC_{50} less than 500 mg/l (measured in soft water) are considered to be toxic

ETV juvenile and adult—EPA bioassay with shaker sample preparation, fathead minnows

Historic data, Envirotemp FR3—OECD TG 203 with solvent sample preparation, juvenile rainbow trout. The fish exhibited *zero mortality* at 1000 mg/l

Historic data, BIOTEMP—EPA bioassay with solvent sample preparation, juvenile rainbow trout

The data shown in Figure 7-1 represent different bioassay procedures (EPA vs. OECD), different test organisms (fathead minnow vs. rainbow trout), and different sample preparations (shaker vs. solvent). Sample preparation appears to have the most influence on test outcome. Solvent sample preparation thoroughly mixes the transformer fluid with water. When added to the bioassay fish tank, this preparation distributes evenly and fish exposed to it die mainly from systemic chemical impact.

Both CPS and ABB entered vendor comments in the Environmental Technology Verification reports on their fluids stating that shaker sample preparation is flawed because it creates a heavy emulsion. When added to the bioassay fish tank, this emulsion floats on the surface, coating the gills of fish swimming through it and causing higher mortality through the combined effects of physical impact (suffocation) and systemic chemical impact. The manufacturers argued that death by systemic chemical impact reflects the true meaning of toxicity, and they reinforced the claim that their fluids are nontoxic when personnel use solvent sample preparation that minimizes physical impact to the fish (see historic data in Figure 7-1).

Manufacturers claim that virgin VOLTESSO 35 mineral oil, XIAMETER PMX-561 silicone fluid, and MIDEL 7131 synthetic ester fluid are nontoxic to aquatic organisms, but offer no supporting data in their product literature. Aquatic toxicity information on Beta Fluid high-temperature hydrocarbon fluid was unavailable. Manufacturers also claim that constituents of synthetic and natural ester fluids do not bioaccumulate in fish.

In-Service Natural Ester Fluids

Environmental Technology Verification tests of aquatic toxicity were not conducted for in-service natural ester fluids.

Operational Impacts

This section includes impacts of workplace exposure to transformer fluids as well as impacts of tests described above that may characterize fluids as toxic, leading to their further classification as hazardous waste.

Shipping, Handling, and Storage

MSDSs provide information about transformer fluids that allow workers to avoid hazardous exposures to toxic substances. MSDSs for all transformer fluids discussed in this report recommend fluid storage in labeled, tightly closed containers placed in cool, dry, isolated and well-ventilated areas, away from sources of ignition and heat. The MSDS for VOLTESSO 35 states that this mineral oil can accumulate static charges which cause sparking that may ignite flammable vapors. It should be stored as recommended above and handled with proper grounding procedures.

According to IEEE C57.147 *IEEE Guide for Acceptance and Maintenance of Natural Ester Fluids in Transformers*, there are no known hazards involved in handling natural ester base oils. The additives in Envirotemp FR3 and BIOTEMP natural ester fluid are also nonhazardous.

Workers are exposed to the chemical constituents of transformer fluids via the following routes:

- *Inhalation*—According to MSDSs and the Environmental Technology Verification report for Envirotem FR3 natural ester fluid, burning transformer fluids emit substances that may be harmful if inhaled (Table 7-1). In case of fire, workers should wear personal protective equipment (PPE) to prevent inhalation. All transformer fluids discussed in this report caused respiratory tract irritation when workers inhaled mists. OSHA defines a slightly higher permissible exposure limit (PEL) to nuisance particulates for workers exposed to Envirotemp FR3 natural ester fluid than for workers exposed to generic mineral oil.

Table 7-1
Thermal Decomposition Products of Transformer Fluids

Transformer Fluid	Products of Incomplete Thermal Decomposition
Mineral oil (generic)	Fumes, smoke, carbon monoxide, aldehydes, sulfur oxides
Beta Fluid® High-Temperature Hydrocarbon	Carbon monoxide, carbon dioxide, volatile hydrocarbons
Silicone (generic)	Fumes, smoke, carbon monoxide, aldehydes, silicon dioxide
MIDEL® 7131 Synthetic Ester	No known hazardous decomposition products
Envirotemp® FR3™ Natural Ester	Carbon monoxide, carbon dioxide, nitrogen oxides, other toxic compounds
BIOTEMP® Natural Ester	Carbon monoxide, carbon dioxide

- *Skin contact*—All transformer fluids discussed in this report caused no, or only mild, irritation when in direct contact with workers' skin.
- *Eye contact*—All transformer fluids discussed in this report caused temporary redness and discomfort when in direct contact with workers' eyes.
- *Ingestion*—All transformer fluids discussed in this report caused gastrointestinal distress—including nausea, stomach pain, and vomiting—when ingested.

Workers are most likely to need PPE to avoid hazardous exposure to toxic substances when handling silicone fluid. For example, workers are advised to wear impervious gloves and chemical goggles when handling some silicone-based fluids listed in the Vermont SIRI MSDS archive. Working with other fluids, such as mineral oil or natural ester fluids, requires a lower level of PPE.

Based on animal studies, the primary component of mineral oil, a hydrotreated light naphthenic petroleum distillate (CAS No. 64742-53-6), is an International Agency for Research on Cancer (IARC) confirmed carcinogen. The primary component of silicone fluid, dimethyl polysiloxane (CAS No. 63148-62-9), causes birth defects in animals. Natural ester fluids contain no IARC-confirmed carcinogens.

Clear communication about the workplace health and safety hazards of transformer fluids is required by OSHA Hazard Communication Standard 49 (CRF1910.1200). Publication of MSDSs to inform workers and the public is required by EPA under the Emergency Planning and Community Right-to-Know Act (EPCRA) (40CFR302.4). These and other regulations pertaining to the use and disposal of transformer fluids are listed in Table 7-2 below.

None of the virgin transformer fluids discussed in this report are classified as hazardous materials under the federal regulations listed in Table 7-2 below. All virgin fluids ship as nonhazardous material under DOT regulations. However, spent transformer fluids testing hazardous under federal or state regulations must be stored in facilities clearly labeled as "used oil–hazardous waste," and must be shipped by registered hazardous waste transporter to authorized storage or treatment facilities.

Added requirements for special storage and handling of VOLTESSO 35 mineral oil, or the need for PPE when using XIAMETER PMX-561 silicone fluid may add to the cost of choosing these transformer fluids.

Operation and Maintenance

Workplace exposure to transformer fluids typically occurs when personnel fill, drain, or sample transformers. Inhalation exposure is unlikely in these settings, but slipping on spilled fluid, splashing fluid into the eyes or onto the skin, or contacting hot oil can cause workplace injury. Companies should maintain occupational health and safety training programs to help workers avoid these problems.

Recovery and Reuse

Spent natural ester fluids must undergo testing for hazardous waste characterization. If the spent fluid is deemed nonhazardous, it may be sold to licensed waste oil recyclers or fat renderers, depending on their criteria for accepting used vegetable oil. A case study of natural ester fluid disposal in the State of California is outlined below.

Disposal

Table 7-2 lists examples of federal regulations governing the use and disposal of natural ester transformer fluids. IEEE C57.147 *IEEE Guide for Acceptance and Maintenance of Natural Ester Fluids in Transformers* states that natural esters are not listed as a hazardous substance or waste by any federal agency.

Table 7-2
Examples of Federal Regulations Governing the Use and Disposal of Natural Ester Transformer Fluids

Federal Regulation	Section	Natural Ester Transformer Fluids
Toxic Substances Control Act (TSCA)	40CFR700	Fluid components are listed, but classified as "not imminently hazardous." Fluids ship as nonhazardous material.
Resource Conservation and Recovery Act (RCRA)	40CFR261.20	Fluids are not a listed waste nor do they exhibit a hazardous characteristic as defined by RCRA (ignitable, corrosive, reactive, or toxic per the Toxicity Characteristic Leaching Procedure).
Used Oil Management Program	40CFR279	Fluids are not subject to this regulation. See Edible Oil Regulatory Reform Act (EORRA).
Oil Pollution Prevention	40CFR112	Fluids are subject to Spill Prevention, Control, and Countermeasure (SPCC) planning and reporting, regardless of hazard classification.
Clean Water Act (CWA)	Section 311	An oil sheen on the surface of navigable waters triggers cleanup, regardless of fluid hazard classification.
Emergency Planning and Community Right-to-Know Act (EPCRA)	40CFR302.4	Fluids are not on the Consolidated List of Chemicals subject to reporting. Material Safety Data Sheets are required.
Occupational Health and Safety Administration (OSHA) Hazard Communication Standard 49	CFR1910.1200	Fluids are classified as nonhazardous. Material Safety Data Sheets are required.
Clean Air Act (CAA)	Section 112	Fluids are classified as nonhazardous.

The State of California offers a case study in requirements for classifying *spent* transformer fluids as hazardous waste. Environmental Technology Verification reports on natural ester fluids list criteria for determining the toxicity of a spent fluid, as defined under the California Code of Regulations, Title 22, Division 4.5, Chapter 11, Article 3, Section 66261.24 (22CCR66261.24). To be characterized as toxic, and therefore hazardous, each spent fluid must

- meet the criteria for hazardous waste designation established in the Code of Federal Regulations, Title 40–Protection of Environment, Part 261.20, Resource Conservation and Recovery Act (RCRA) (40CFR261.20),
- contain a substance listed in 22CCR66261.24, as determined by the Waste Extraction Test (WET),
- have a 96-hour acute aquatic LC_{50} of less than 500 mg/l or contain any of the substances listed in 22CCR66261.24(a)(7),
- have an acute oral lethal dose (LD_{50}) of less than 5,000 mg/kg,
- have an acute dermal LD_{50} of 4,300 mg/kg, and/or
- have an acute inhalation LC_{50} of less than 10,000 ppm as a gas or vapor.

Note that fluids deemed nonhazardous by federal criteria (40CFR261.20) but hazardous by State of California criteria (22CCR66261.24) must be managed as used oil per 22CCR66179.1 with limits on PCB and halogen content. When natural ester fluids meeting these criteria are removed from a transformer, filtered, and reused on-site as transformer fluids, they are exempt from management as used oil.

Environmental Technology Verification bioassays using virgin natural ester fluids suggest that *spent* natural ester fluids may, under some conditions, be classified as hazardous waste. In California, where the Environmental Technology Verification tests were performed, insoluble waste samples undergo both screening and final bioassays for acute aquatic toxicity. Samples are prepared for the screening bioassay by shaker, ultrasound, and solvent procedures. The procedure yielding the most conservative LC_{50} result is then used in the final bioassay. Environmental Technology Verification testers from CalEPA/DTSC purposely chose shaker sample preparation as the most conservative procedure. If their choice was correct, spent natural ester fluids may have to demonstrate nontoxicity under this procedure to escape treatment as hazardous waste in California. Requirements in other states may vary.

Non-PCB transformer fluids are not listed as RCRA hazardous waste (40CRF261) at disposal. Spent Envirotemp FR3 and BIOTEMP natural ester fluids are not listed as RCRA hazardous waste, but they may meet local or state definitions of hazardous waste, as described in the State of California case study above. Finally, spent MIDEL 7131 synthetic ester fluid is listed as hazardous waste per the European Waste Catalogue 13 03 09 and requires incineration at disposal.

Spent transformer fluids should be characterized for concentrations of metals using EPA Method 1311 and the Toxicity Characteristic Leaching Procedure (TCLP). If PCB contamination due to retrofill is suspected, spent transformer fluids should also be characterized for PCBs using EPA Method 8082. Spent fluids that test hazardous per RCRA criteria must be managed as hazardous waste. This requirement extends to materials used in spill cleanup. Companies should consult with local, state, and federal authorities to ensure compliance with all regulations governing fluid disposal.

Cleanup

During routine maintenance, personnel should check for transformer fluid leaks. Workers can clean up minor leaks or spills using absorbent rags and petroleum solvents for mineral oils, or household detergents for natural ester fluids. Stubborn films of polymerized natural esters may require the use of a manufacturer-recommended degreaser plus steam or hot water spray. One company responding to EPRI’s 2009 survey noted a rancid odor associated with hot, spilled Envirotemp FR3, and another company said the odor impeded cleanup.

Cleaning up spills on waterways is much more challenging. Remediation of large spills involves containing the fluid within floating booms or dikes, and then removing it by absorption, pumping, or skimming. If containment is impractical, workers can use chemical dispersants listed on EPA’s National Contingency Plan Product Schedule to mix the fluid into the water column. Collected fluids are reclaimed or incinerated.

Spills on soil are typically regulated by state and local authorities. It may be possible to negotiate site-specific, risk-based cleanups of natural ester fluid spills with local regulators when those spills do not reach sources of drinking water or navigable waterways.

Federal Oil Pollution Prevention regulations (40CFR112) apply to all transformer fluids discussed in this report, regardless of composition or hazard classification. Under these regulations, facilities that "could be expected to discharge oil into or upon the navigable water of the United States or adjoining shorelines" and meet certain underground and aboveground oil storage capacity requirements must prepare and submit Spill Prevention, Control, and Countermeasure (SPCC) plans. If these facilities transfer qualifying volumes of oil over water and meet various risk criteria, they must also prepare and submit facility response plans (FRPs). An FRP outlines rehearsed responses to worst-case oil spills—from initial reporting to the National Response Center through containment and cleanup. Reporting is triggered by a violation of water quality standards, a film or sheen appearing on the water surface or on nearby shorelines, and/or sludge appearing below the water surface or on the shoreline.

IEEE C57.147 *IEEE Guide for Acceptance and Maintenance of Natural Ester Fluids in Transformers* states:

> "Currently, the U.S. EPA Spill Prevention, Control, and Countermeasure (SPCC) regulation (40CRF112) makes no distinction between mineral oils and vegetable oils, except for possible reduction in spill remediation requirements."

One 2009 EPRI survey respondent noted that Envirotemp FR3 natural ester fluid "is not specifically exempt from any regulations, such as the spill reporting and cleanup requirements, under the Clean Water Act." Another found that the New York State Department of Environmental Conservation "requires cleanups to be the same as for mineral oil." As discussed above, spills of natural ester fluids in California are assumed to be hazardous until they have been characterized and shown to be nonhazardous. Disposal options relax if the spills test nonhazardous, but cleanup requirements remain the same.

New options for cleaning up natural ester fluid spills would significantly reduce costs for companies choosing these environmentally acceptable transformer fluids. According to an article published by Waverly Light and Power (Waverly Light and Power 2010), "…the EPA has not yet made any significant differential in the Spill Prevention, Control and Countermeasure (SPCC) requirement for non-edible oils versus edible oils." However, "The EPA has expressed that they are studying the matter and they are considering possibly differentiating it in the future."

Biodegradability

Measured Values

Biodegradability describes the rate and extent of transformer fluid decomposition in the presence of bacterial organisms. There are several test methods for measuring the aerobic biodegradation of transformer fluids released into freshwater environments. Test methods discussed in this report include:

- CEC L-33-A-93 (Biodegradability of Two-Stroke Cycle Outboard Engine Oils in Water)—This Coordinating European Council (CEC) method compares the biodegradation potential of a transformer fluid with that of a standard test oil, both inoculated with sewage microbes. The test expresses biodegradability as a percentage difference in the residual oil content of poisoned and test flasks. This outdated method is undergoing revision.

- OECD 301B (Ready Biodegradability)—This European Organization for Economic Cooperation and Development (OECD) method measures the amount of carbon dioxide (CO_2) generated when bacterial organisms consume transformer fluid. The test expresses biodegradability as a percentage of CO_2 that theoretically could be produced.
- EPA Test Method 560/6/-82-003 (Aerobic Aquatic Biodegradability)—This EPA method is equivalent to OECD 301B.
- EPA Test Method OPPTS 835.3110 (Ready Biodegradability)—This EPA Office of Prevention, Pesticides and Toxic Substances (OPPTS) method is equivalent to OECD 301B.
- OECD 301F (Ready Biodegradability)—This OECD method measures the amount of oxygen (O_2) taken up when bacterial organisms consume transformer fluid. The test expresses biodegradability as a percentage of O_2 that theoretically could be taken up.

According to EPA, superior performance on a ready biodegradability test predicts a transformer fluid's rapid and ultimate biodegradation in aerobic aquatic environments. To be classified as "readily biodegradable," fluids must reach 60% biodegradation within 10 days of achieving 10% biodegradation, and must be at least 60% biodegraded by day 28 of the test. "Ultimate biodegradability" is the complete breakdown of an organic compound—such as transformer fluid—to CO_2, water, oxides or mineral salts, and normal metabolic products of microorganisms.

Virgin Fluids

Figure 7-2 presents data from the product literature describing the aquatic biodegradability of virgin transformer fluids tested by CEC L-33-A-93 for 21 days. Envirotemp FR3 and BIOTEMP natural ester fluids show superior biodegradability, followed by MIDEL 7131 synthetic ester fluid. Beta Fluid high-temperature hydrocarbon fluid and VOLTESSO 35 mineral oil hover in the 20–30% biodegradability range, while XIAMETER PMX-561 silicone fluid has very limited biodegradability.

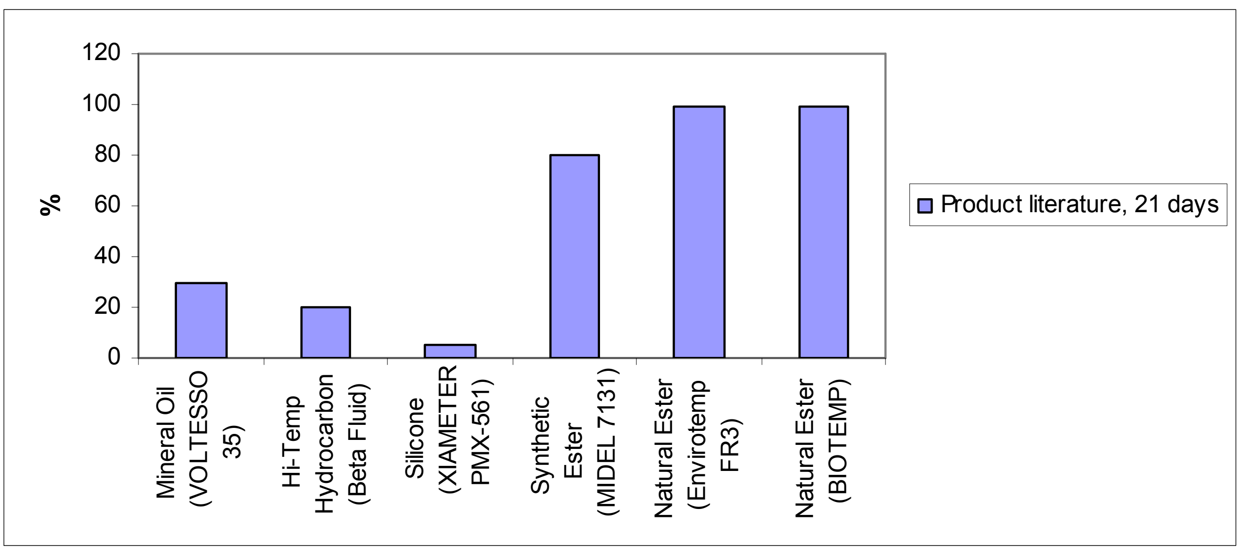


Figure 7-2
Virgin Fluids: Aquatic Biodegradability—Product Literature

CEC L-33-A-93 test results from Appendix D

Results of Environmental Technology Verification tests and other independent assessments (Figure 7-3) confirm the relative biodegradability of virgin transformer fluids seen in the product literature, although the test methods used are not strictly comparable. A biodegradability of 120% for Envirotemp FR3 natural ester fluid probably reflects CO_2 losses from control samples; historical values have averaged 99%, which is the manufacturer's minimum (not shown). BIOTEMP natural ester fluid also meets its manufacturer's minimum of 97% biodegradability (not shown).

The literature explicitly states that Envirotemp FR3 and BIOTEMP natural ester fluids, and MIDEL 7131 synthetic ester fluid meet the strict criteria for EPA classification as readily biodegradable fluids. CPS claims that Envirotemp FR3 should be classified as ultimately biodegradable because it completely biodegrades after 45 days (per unspecified EPA standard test).

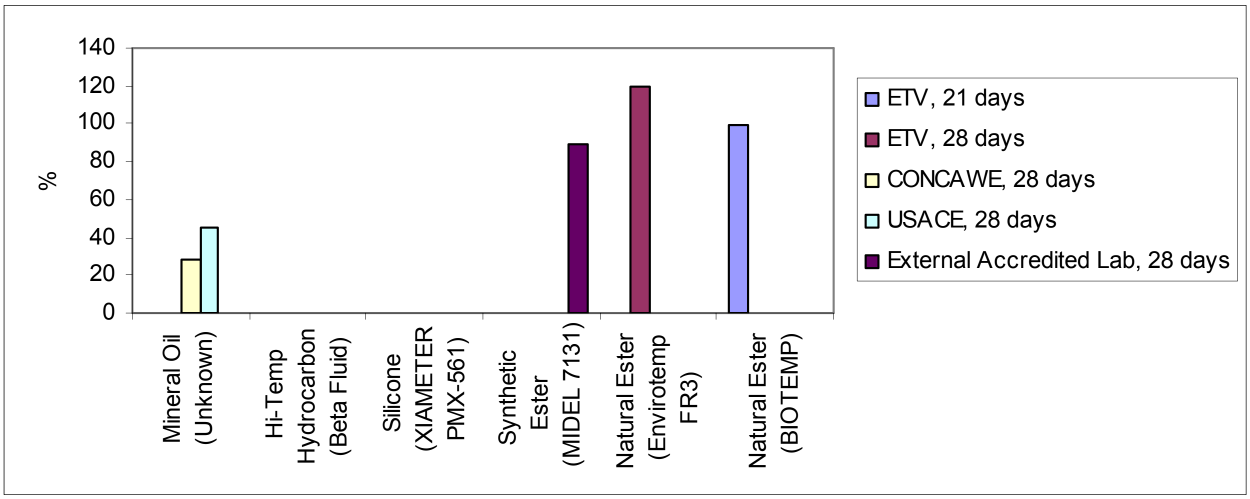


Figure 7-3
Virgin Fluids: Aquatic Biodegradability—Independent Environmental Tests

Test results from Appendix E; some values were unavailable
Mineral oil—OECD 301B, Conservation of Clean Air and Water-Europe (CONCAWE)
Mineral oil—EPA Method 560/6/-82-003, U.S. Army Corps of Engineers (USACE)
MIDEL 7131—OECD 301F, External Accredited Lab
Envirotemp FR3—EPA Method OPPTS 835.3110, Environmental Technology Verification (ETV)
BIOTEMP—CEC L-33-A-93, Environmental Technology Verification (ETV)

In-Service Natural Ester Fluids

Environmental Technology Verification tests of biodegradability were not conducted for in-service natural ester fluids.

Operational Impacts

Disposal

When remediation by biodegradation is a regulatory option for a spill site, owners can avoid the high cost of excavation and disposal. Disposal of a transformer fluid or its cleanup residue as hazardous or nonhazardous material is not influenced by its biodegradability.

Cleanup

Transformer fluids that readily biodegrade in laboratory tests require similar conditions to achieve complete biodegradation in the field. These conditions include adequate amounts of water, oxygen, microorganisms, and heat—in water or soil. Other site-specific factors that influence the rate and extent of biodegradation include climate, geology, pH, oil dispersal, the presence of other chemicals, soil characteristics, and available nutrients.

Transformer fluids that are not readily biodegradable (mineral oil, high-temperature hydrocarbon fluid, and silicone fluid) are likely to persist in the environment and may require source removal as part of spill remediation at some sites. Source removal may involve skimming or absorbing oil from the surface of water bodies, or excavating contaminated soil and hauling it away for disposal.

In contrast, transformer fluids that are readily biodegradable (synthetic and natural ester fluids) may biodegrade *in situ* after a spill. To hasten natural biodegradation in soil and groundwater, companies can use fertilizing or seeding. Fertilizing adds nutrients to stimulate the growth of native microorganisms, while seeding adds microorganisms to the indigenous population. Since states typically have jurisdiction over spills impacting soils, state and local regulators may be amenable to negotiating site-specific remediation programs for readily biodegradable fluid spills that do not impact surface waters.

Although synthetic and natural ester fluids biodegrade quickly in water, current federal regulations ensure that biodegradation cannot be used to ameliorate spills impacting navigable surface waters. Under provisions of the federal Clean Water Act (Discharge of Oil regulation), transformer fluid spills that create a sheen on the water surface require immediate reporting, containment, and cleanup by removal. The federal statue defines the term “oil” broadly, applying the sheen rule to both petroleum and nonpetroleum (that is, vegetable) oils.

Since natural ester fluids are regulated under the Edible Oil Regulatory Reform Act (EORRA) instead of the Federal Regulation of Used Oils (40CRF279), they are good candidates for future regulatory relief from federal spill and cleanup requirements. Such relief might be based, in part, on their ready biodegradability.

Spill cleanup costs may be reduced when state and local regulators are amenable to negotiating site-specific remediation programs that take transformer fluid biodegradability into account. In such cases, synthetic and natural ester fluids would offer a cost advantage.

Transport and Fate

Measured Values

In the event of accidental releases or spills, the transport and fate properties of transformer fluids will determine their impact on the environment. These properties include:

- *Aqueous Solubility*—A water-soluble transformer fluid is easily transported in surface water and groundwater and readily leaches through the soil. Low aqueous solubility is a desirable property of transformer fluids.
- *Mobility*—Typical transformer fluids are mobile in the environment, due to their relatively low density and low viscosity. Most transformer fluids are lighter-than-water, nonaqueous-phase liquids (LNAPLs) that float on the water surface. It is also the case that less-viscous transformer fluids are more mobile. Dense, highly viscous fluids have the least potential for migration in the environment.
- *Volatility*—A transformer fluid that readily vaporizes is volatile. Most transformer fluids are not very volatile; they do not release harmful vapors or nuisance odors during normal use. Low volatility is a desirable property of transformer fluids.

Table 7-3 summarizes available information about the transport and fate properties of transformer fluids discussed in this report. All fluids are insoluble or have very low solubility in water. All fluids are less dense than water. Fluids have low to moderate viscosity except Beta Fluid, a high-temperature hydrocarbon with very high viscosity at lower temperatures (0–40 ºC). Finally, all fluids have very low to low volatility.

Table 7-3
Transport and Fate Properties of Transformer Fluids

Fluid Type	Aqueous Solubility[A]	Mobility		Volatility[C]
		Relative Density[B]	Kinematic Viscosity[B] at 40 ºC	
VOLTESSO 35 Mineral Oil	Low	Less than water	Very low	Very low
Beta Fluid® High-Temperature Hydrocarbon	Very low	Less than water	Very high	Low
XIAMETER® PMX-561 Silicone	Extremely low	Less than water	Moderate	Very low
MIDEL® 7131 Synthetic Ester	Insoluble	Less than water	Moderate	Low
Envirotemp® FR3™ Natural Ester	Negligible	Less than water	Moderate	Very low
BIOTEMP® Natural Ester	Insoluble	Less than water	Moderate	Very low

[A] Material Safety Data Sheets

[B] See virgin fluids, Section 4

[C] EPRI, 1998. *Options for Reducing Environmental-Related Utility Costs Associated With Dielectric Fluids Employed in Cables and Transformers*, Palo Alto, CA, TR-111722.

Operational Impacts

Cleanup

The transformer fluids discussed in this report dissolve slightly or not at all in surface water and groundwater. Constituents of fluids that remain in surface water for any length of time will partition to sediment. Sediment cleanup might involve excavation and removal, or capping. Since these fluids do not dissolve, their constituents are unlikely to leach into groundwater. Thus, local spills impacting only the soil may require minimal cleanup.

Transformer fluids that are less dense than water float on the surface, forming sheens, slicks, or nonaqueous-phase liquid (NAPL) layers that can migrate to land and foul the shoreline. Visible sheen triggers immediate reporting and cleanup—which typically involves absorbing, skimming, or pumping the fluid. If transformer fluid remains on the water surface, it can harm aquatic organisms by depriving them of dissolved oxygen in the water column. Under some conditions, transformer fluids can form NAPL layers on top of the water table that will contaminate groundwater and soil gas for years.

Transformer fluids of very low viscosity at ambient temperatures, such as VOLTESSO 35 mineral oil, percolate easily through soils until they reach groundwater, surface water, or impermeable material. As fluids become more viscous, they move less freely through soils. Beta Fluid high-temperature hydrocarbon fluid has very high viscosity, which may confer the advantage of low mobility and easy cleanup in the case of spills or accidental releases.

The transformer fluids discussed in this report have very low to low volatility. Thus, it is unlikely that nuisance odors by themselves will prompt cleanup or that workers will be exposed to toxic vapors while dealing with spilled fluids. However, workers have reported nuisance odors emanating from hot natural ester fluid spills.

Transformer fluid spills that do not violate water quality standards, do not create a film or sheen on the water surface or shoreline, and do not introduce sludge into the water or onto the shoreline may be candidates for site-specific, risk-based cleanup. Implementing this remediation strategy requires a full site characterization that takes spilled fluid transport and fate into account. It also requires a negotiated agreement among site owners and regulators representing local, state, and in some cases federal requirements. When appropriate and successful, this strategy is cost-effective.

8
SUMMARY AND COST CONSIDERATIONS

This section summarizes the advantages and disadvantages of environmentally acceptable transformer fluids compared with those of mineral oil, and discusses cost considerations in choosing a transformer fluid.

Comparative Advantages and Disadvantages of Environmentally Acceptable Transformer Fluids

The following paragraphs compare the performance of each environmentally acceptable transformer fluid discussed in this report with that of VOLTESSO 35 mineral oil. Each comparison states relative advantages and disadvantages, as described in the product literature and corroborated by Environmental Technology Verification tests for natural ester fluids. The comparisons consider the physical, dielectric, chemical, and environmental properties of virgin fluids. Sections 4 through 7 above offer detailed descriptions of fluid differences and their impacts, as well as available information about in-service fluid performance.

Beta Fluid High-Temperature Hydrocarbon Fluid

Advantages

- Flash and fire points—higher heat is required to trigger flashover or ignition
- Dielectric breakdown voltage (1-mm gap)—better withstands high electric field stress
- Dielectric breakdown voltage (impulse)—better withstands transient voltage stresses imposed by lightning or power surges

Disadvantages

- Color—more opaque
- Pour point—stops pouring sooner, as temperature cools
- Kinematic viscosity—does not flow as freely
- Gassing tendency—releases hydrogen gas under electrical stress
- Volume resistivity—has lower insulating capacity
- Biodegradability—biodegrades less readily

XIAMETER PMX-561 Silicone Fluid

Advantages

- Flash and fire points—higher heat is required to trigger flashover or ignition
- Relative permittivity—more easily equalizes electrical stress between fluid and insulation
- Dissipation factor—better prevents heating that deteriorates insulation over time

- Neutralization (acid) number—less likely to form acid degradation products

Disadvantages

- Pour point—stops pouring sooner, as temperature cools
- Kinematic viscosity—does not flow as freely
- Coefficient of thermal expansion—expands more quickly as temperature rises
- Dielectric breakdown voltage (minimum)—less able to withstand high electric field stress
- Volume resistivity—has lower insulating capacity
- Biodegradability—biodegrades less readily

MIDEL 7131 Synthetic Ester Fluid

Advantages

- Flash and fire points—higher heat is required to trigger flashover or ignition
- Dielectric breakdown voltage (minimum)—better withstands high electric field stress
- Relative permittivity—more easily equalizes electrical stress between fluid and insulation
- Water content—has higher water content but also a much higher threshold for 50% saturation, the value at which fluid dielectric strength starts to fall
- Biodegradability—biodegrades more readily

Disadvantages

- Kinematic viscosity—does not flow as freely
- Dissipation factor—allows heating that deteriorates insulation over time
- Volume resistivity—has lower insulating capacity
- Neutralization (acid) number—more likely to form acid degradation products

Envirotemp FR3 and BIOTEMP Natural Ester Fluids

Advantages

- Flash and fire points—higher heat is required to trigger flashover or ignition
- Heat capacity and thermal conductivity—more efficient coolants
- Dielectric breakdown voltage (1-mm gap)—better withstand high electric field stress
- Gassing tendency—adsorb more hydrogen gas under electrical stress
- Relative permittivity—more easily equalize electrical stress between fluid and insulation
- Water content—have higher water content but also a much higher threshold for 50% saturation, the value at which fluid dielectric strength starts to fall
- Biodegradability—biodegrade more readily

Disadvantages

- Pour point—stop pouring sooner, as temperature cools
- Kinematic viscosity—do not flow as freely

- Dielectric breakdown voltage (impulse)—less able to withstand transient voltage stresses imposed by lightning or power surges
- Dissipation factor—allow heating that deteriorates insulation over time
- Volume resistivity—have lower insulating capacity
- Neutralization (acid) number—more likely to form acid degradation products
- Interfacial tension—more likely to form soluble polar contaminants
- Aquatic toxicity—fall within the toxic range of the California Toxicity Criterion

Cost Considerations

In its *Final Guidance on Environmentally Preferable Purchasing for Executive Agencies* (EPA 1999), EPA states five principles:

- Include environmental considerations
- Emphasize pollution prevention
- Examine multiple environmental attributes throughout the product and service's life cycle
- Compare environmental impacts
- Collect accurate and meaningful information about the environmental performance of products and services

With EPA's principles in mind, this report provides information to support the purchasing decisions of companies considering environmentally acceptable transformer fluids.

Sections 4 through 7 above offer qualitative examples of increased costs due to operational impacts created by fluid properties. For example, special storage provisions to keep fluids viable at low temperatures may add to the cost of using transformer fluids with high pour points.

Environmental Technology Verification reports describe the first cost of purchasing a new transformer filled with natural ester fluid or mineral oil. The natural ester fluid-filled transformer costs about 1.2–1.3 times more than a comparable mineral-oil filled transformer. In terms of price per gallon (2002), Envirotemp FR3 natural ester fluid costs $5–$8 more than mineral oil and BIOTEMP natural ester fluid costs $4–$9 more than mineral oil, depending on volume purchased. Prices for mineral oil typically range from $2–$3 per gallon (2002). The price difference between natural ester fluids and mineral oil may have decreased since 2002, when the Environmental Technology Verification reports were published.

In a 2005 paper, General Electric Specification Engineer Dave Hart noted that Beta Fluid high-temperature hydrocarbon fluid costs 1.2 times more than mineral oil, and generic silicone fluid costs 1.3 times more (Hart 2005). No cost multiplier is available for MIDEL 7131, although its high cost compared with mineral oil typically limits the use of this synthetic ester to specialty applications.

A life-cycle cost analysis would consider fluid costs over a typical 20-year transformer life span. Some of those costs would be related to

- initial acquisition:
- shipping, handling, and storage;
- installation;
- operation and maintenance;
- recovery and reuse;
- disposal;
- cleanup;
- environmental toxicity and hazardous waste characterization;
- worker health and safety;
- biodegradability; and
- environmental transport and fate.

Life-cycle costs are specific to the system and regulatory setting under analysis.

Manufacturers of natural ester fluids claim that the use of their products generates a total life-cycle cost saving compared with the use of other fluid types. Data from 20 years of natural ester fluid use are lacking, so this claim is presently unsubstantiated. However, if Envirotemp FR3 natural ester fluid does extend insulation life 5–8 times as demonstrated in accelerated aging tests, it will prolong transformer service life and delay asset replacement. This would be a significant contribution to life-cycle cost saving. But this contribution would be overshadowed by an EPA regulatory decision to ease spill cleanup requirements for natural ester transformer fluids.

Environmental Technology Verification analyses of natural ester fluids offer cost comparisons relevant to life-cycle cost estimation. Waste characterization costs for natural ester fluids and mineral oil will be similar, unless the mineral oil has PCB contamination. Disposal costs for natural ester fluids and mineral oil will be similar, until more data are available to characterize spent natural ester fluids. Substituting natural ester fluid for mineral oil requires no transformer modifications, but the retrofill fluid will cost more than mineral oil.

As utilities gain more experience with environmentally acceptable transformer fluids, they have a better basis for making purchasing decisions. Here are some of the comments from companies responding to EPRI's 2009 survey:

- "Envirotemp FR3 oil costs approximately 10–20% more than mineral oil."
- "We are NOT buying any special fluids mainly due to cost."
- "[Our] EE Procurement Group unilaterally decided to make all new transformer purchases to include the vegetable oil fluids. They believed that the incremental cost was justified by improved energy efficiency. [One manager] indicated that federal energy efficiency standards for transformers do not include vegetable oil. [Another manager] is investigating the decision, as the cost benefit is not clear."
- "We could never get past the additional cost, particularly since cleanups wouldn't necessarily be any easier."

- “We are using Envirotemp FR3 and BIOTEMP as alternatives to silicone transformers in indoor locations. The cost increment, coupled with lack of savings from spill cleanup (the fluids are treated like mineral oil), has resulted in lack of interest in broader use.”

9
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A
VIRGIN AND IN-SERVICE NATURAL ESTER FLUIDS—DATA FROM ENVIRONMENTAL TECHNOLOGY VERIFICATION TESTS

Table A-1 lists the in-service transformers providing samples for Environmental Technology Verification tests of natural ester fluids.

Table A-1
In-Service Natural Ester Fluids—Transformers Providing Samples for Environmental Technology Verification Tests

Owner	Type	Transformer	Rating	Primary Voltage	Secondary Voltage	Temp-Rise	In-Service Date
Envirotemp FR3							
Cooper	3-phase pad mounted transformer	#1	225	5	480	65	July 1996
Cooper	3-phase pad mounted transformer	#2	225	5	480	65	July 1996
Cooper	3-phase pad mounted transformer	#3	225	21	480	65	March 2000
Texas Instruments	3-phase pad mounted transformer	#4	2500	21	480	65	May 2000
BIOTEMP							
PG&E	3-phase vault network transformer	#1	1,000	12,000	480	65	March 2000
PG&E	3-phase vault network transformer	#2	1,000	12,000	480	65	March 2000
PG&E	3-phase vault network transformer	#3	1,000	12,000	480	65	March 2000
ABB	3-phase RSL insulated unit substation	#4	1,000	—	—	65	June 2000

Table A-2 displays data from Environmental Technology Verification (ETV) tests describing the properties of virgin and in-service natural ester fluids. Some tests were omitted.

Fluid manufacturers specified performance limits for the products they submitted to CalEPA/DTSC for testing. Note that these limits may differ from the typical ASTM test values for fluid properties published in product literature (Appendix D).

Table A-2
Virgin and In-Service Natural Ester Fluids—Data From Environmental Technology Verification Tests

Properties	Units	Test Method	Condition	Envirotemp® FR3™[A]				BIOTEMP®[B]			
				Virgin		In-Service		Virgin		In-Service	
				Cooper Power Systems	ETV Average[C]	Cooper Power Systems	ETV Average[C]	ABB	ETV Average[D]	ABB	ETV Average[C]
Physical											
Flash point	°C	ASTM D92		320 minimum	328	320 minimum	324	300 minimum	331	320 minimum	332
Fire point	°C	ASTM D92		350 minimum	363	350 minimum	364	300 minimum	360	300 minimum	363
Pour point	°C	ASTM D97		-18 maximum	-18	—	—	-25 maximum	-17	—	—
Kinematic viscosity	cSt	ASTM D445	0 °C	—	188	—	—	300 maximum	276	—	—
			40 °C	35 maximum	33	—	—	45 maximum	41	—	—
			100 °C	8.5 maximum	7.9	—	—	10 maximum	8.6	—	—

Table A-2 (continued)
Virgin and In-Service Natural Ester Fluids—Data From Environmental Technology Verification Tests

Properties	Units	Test Method	Condition	Envirotemp® FR3™[A]				BIOTEMP®[B]			
				Virgin		In-Service		Virgin		In-Service	
				Cooper Power Systems	ETV Average[C]	Cooper Power Systems	ETV Average[C]	ABB	ETV Average[D]	ABB	ETV Average[C]
Electrical											
Dielectric breakdown voltage (minimum)	kV	ASTM D877		30 minimum	45	—	—	30 minimum	50	—	—
Dielectric breakdown voltage (gap)	kV	ASTM D1816	1-mm gap	20 minimum	37[E]	—	—	28 minimum	37	—	—
Dielectric breakdown voltage (impulse)	kV	ASTM D3300		—	168	—	—	100 minimum	185	—	—
Dissipation (power) factor	%	ASTM D924	25 ºC	0.15 maximum	0.14	1.0 maximum	0.15	0.05 maximum	0.08	0.05 maximum	0.14
			100 ºC	—	2.89			2.00 maximum	1.67		
Electrical conductivity	pS/m	ASTM D4308		—	—	—	13.5	—	—	2.0 minimum	15.2

Table A-2 (continued)
Virgin and In-Service Natural Ester Fluids—Data From Environmental Technology Verification Tests

Properties	Units	Test Method	Condition	Envirotemp® FR3™[A]				BIOTEMP®[B]			
				Virgin	In-Service			Virgin		In-Service	
				Cooper Power Systems	ETV Average[C]	Cooper Power Systems	ETV Average[C]	ABB	ETV Average[D]	ABB	ETV Average[C]
Chemical											
Water content	ppm	ASTM D1533		75 maximum	55	400 maximum	57	150 maximum	79	150 maximum	32
Oxidation stability	sludge, wt%	ASTM D2440	72 h @ 100 ºC	—	—	—	—	—	—	—	—
			164 h @ 110 ºC	—	—	—	—	—	—	—	—
	neutralization (acid) number, mg KOH/g		72 h @ 100 ºC					—	—	—	—
			164 h @ 110 ºC	—	—	—	—	—	—	—	—
Neutralization (acid) number	mg KOH/g	ASTM D974		0.07 maximum	0.03	2.50 maximum	0.04	—	—	—	—
Interfacial tension	dynes/cm	ASTM D971	25 ºC	18 minimum	28	18 minimum	25	—	—	—	—

Table A-2 (continued)
Virgin and In-Service Natural Ester Fluids—Data From Environmental Technology Verification Tests

[A] EPA-CalEPA/DTSC, 2002a. *Environmental Technology Verification Report: Cooper Power Systems Envirotemp® FR3™ Vegetable Oil-Based Insulating Dielectric Fluid*, California Environmental Protection Agency, Department of Toxic Substances Control, Office of Pollution Prevention and Technology Development, Sacramento, California 94812-0806, DTSC R-02-02 (EPA 600/R-02/042), May.

[B] EPA-CalEPA/DTSC, 2002b. *Environmental Technology Verification Report: ABB Inc. BIOTEMP® Vegetable Oil-Based Insulating Dielectric Fluid,* California Environmental Protection Agency, Department of Toxic Substances Control, Office of Pollution Prevention and Technology Development, Sacramento, California 94812-0806, DTSC R-02-03 (EPA 600/R-02/043), June.

[C] Average of 4 samples

[D] Average of 10 samples (viscosity = average of 9 samples)

[E] Gap size unspecified

B
ASTM STANDARD TEST METHODS

Table B-1 lists the ASTM standard test methods used to obtain fluid property values discussed in this report.

Table B-1
ASTM Standard Test Methods

Test Method	Title
ASTM D92	Standard Test Method for Flash and Fire Points by Cleveland Open Cup Tester
ASTM D97	Standard Test Method for Pour Point of Petroleum Products
ASTM D445	Standard Test Method for Kinematic Viscosity of Transparent and Opaque Liquids (and Calculation of Dynamic Viscosity)
ASTM D877	Standard Test Method for Dielectric Breakdown Voltage of Insulating Liquids Using Disk Electrodes
ASTM D924	Standard Test Method for Dissipation Factor (or Power Factor) and Relative Permittivity (Dielectric Constant) of Electrical Insulating Liquids
ASTM D971	Standard Test Method for Interfacial Tension of Oil Against Water by the Ring Method
ASTM D974	Standard Test Method for Acid and Base Number by Color-Indicator Titration
ASTM D1169	Standard Test Method for Specific Resistance (Resistivity) of Electrical Insulating Liquids
ASTM D1275B	Standard Test Method for Corrosive Sulfur in Electrical Insulating Oils
ASTM D1298	Standard Test Method for Density, Relative Density (Specific Gravity), or API Gravity of Crude Petroleum and Liquid Petroleum Products by Hydrometer Method
ASTM D1500	Standard Test Method for ASTM Color of Petroleum Products (ASTM Color Scale)
ASTM D1524	Standard Test Method for Visual Examination of Used Electrical Insulating Oils of Petroleum Origin in the Field
ASTM D1533	Standard Test Methods for Water in Insulating Liquids by Coulometric Karl Fischer Titration
ASTM D1816	Standard Test Method for Dielectric Breakdown Voltage of Insulating Oils of Petroleum Origin Using VDE Electrodes
ASTM D1903	Standard Practice for Determining the Coefficient of Thermal Expansion of Electrical Insulating Liquids of Petroleum Origin, and Askarels

Table B-1 (continued)
ASTM Standard Test Methods

Test Method	Title
ASTM D2300	Standard Test Method for Gassing of Insulating Liquids Under Electrical Stress and Ionization (Modified Pirelli Method)
ASTM D2440	Standard Test Method for Oxidation Stability of Mineral Insulating Oil
ASTM D2717	Standard Test Method for Thermal Conductivity of Liquids
ASTM D2766	Standard Test Method for Specific Heat of Liquids and Solids
ASTM D3300	Standard Test Method for Dielectric Breakdown Voltage of Insulating Oils of Petroleum Origin Under Impulse Conditions
ASTM D4059	Standard Test Method for Analysis of Polychlorinated Biphenyls in Insulating Liquids by Gas Chromatography

C

VIRGIN AND IN-SERVICE NATURAL ESTER FLUIDS—STANDARD SPECIFICATIONS

Table C-1 shows limits of transformer fluid properties defined by standard specifications for virgin and in-service natural ester fluids. ASTM D6871 *Standard Specification for Natural (Vegetable Oil) Ester Fluids Used in Electrical Apparatus* defines limits for virgin fluids. IEEE C57.147 *IEEE Guide for Acceptance and Maintenance of Natural Ester Fluids in Transformers* defines limits for in-service fluids based on transformer voltage class.

Table C-1
Virgin and In-Service Natural Ester Fluids—Standard Specifications

Properties	Units	Test Method	Condition	Natural Ester Fluids			
				Virgin	In-Service		
				ASTM D6871[A]	IEEE C57.147[B]		
					Transformer Voltage Class		
					≤ 69 kV	> 69 kV < 230 kV	≥ 230 kV
Physical							
Color	L	ASTM D1500		1.0 maximum	—	—	—
Visual appearance		ASTM D1524		bright & clear	—	—	—
Flash point	ºC	ASTM D92		275 minimum	—	—	—
Fire point	ºC	ASTM D92		300 minimum	300 minimum	300 minimum	300 minimum
Pour point	ºC	ASTM D97		-10 maximum	—	—	—
Kinematic viscosity	cSt	ASTM D445	0 ºC	500 maximum	—	—	—
			40 ºC	50 maximum	—	—	—
			100 ºC	15 maximum	—	—	—
Heat capacity (specific heat)	cal/g ºC	ASTM D2766	20 ºC	0.53[C]	—	—	—
Thermal conductivity	W/m-K	ASTM D2717	20 ºC	0.17[C]	—	—	—
Relative density (specific gravity)	kg/m^3	ASTM D1298	15 ºC	0.96 maximum	—	—	—
Coefficient of thermal expansion	volume/ºC	ASTM D1903	25–100 ºC	0.00075[C]	—	—	—

Table C-1 (continued)
Virgin and In-Service Natural Ester Fluids—Standard Specifications

Properties	Units	Test Method	Condition	Natural Ester Fluids			
				Virgin	In-Service		
				ASTM D6871[A]	IEEE C57.147[B]		
					Transformer Voltage Class		
					≤ 69 kV	> 69 kV < 230 kV	≥ 230 kV
Electrical							
Dielectric breakdown voltage (minimum)	kV	ASTM D877		30 minimum	—	—	—
Dielectric breakdown voltage (gap)	kV	ASTM D1816	1-mm gap	20 minimum [D]	23 minimum	28 minimum	30 minimum
			2-mm gap	35 minimum [D]	40 minimum	47 minimum	50 minimum
Dielectric breakdown voltage (impulse)	kV	ASTM D3300		130 minimum	—	—	—
Dissipation (power) factor	%	ASTM D924	25 ºC	0.2 maximum	—	—	—
			100 ºC	4.0 maximum	—	—	—
Gassing tendency	µl/min	ASTM D2300		0 maximum	—	—	—
Relative permittivity (dielectric constant)	K	ASTM D924	25 ºC	3.2 [C]	—	—	—
Chemical							
Water content	ppm	ASTM D1533		200 maximum	[E]	[E]	[E]
Neutralization (acid) number	mg KOH/g	ASTM D974		0.06 maximum	—	—	—
Corrosive sulfur		ASTM D1275B		nil	—	—	—
PCB content	ppm	ASTM D4059		not detectable	—	—	—

[A] ASTM D6871, 2008. *Standard Specification for Natural (Vegetable Oil) Ester Fluids Used in Electrical Apparatus*, ASTM International, West Conshohocken, PA.

[B] IEEE C57.147, 2008. *IEEE Guide for Acceptance and Maintenance of Natural Ester Fluids in Transformers*, Institute of Electrical and Electronics Engineers, New York, NY.

[C] average of typical values, not a mandatory limit

[D] Sampled from bulk tanker. IEEE C57.147 states, "This value is based on the mandatory processing of bulk oil shipments prior to filling transformers. The processing shall include small particle filtering, degasification, and moisture extraction." Samples from drums or totes have more stringent limits.

[E] IEEE states that the "recommended limit is application- and user-specific."

D

VIRGIN FLUIDS—DATA FROM PRODUCT LITERATURE

Table D-1 displays data from product literature describing the properties of virgin transformer fluids. The data represent typical values suitable for relative comparisons among fluids.

The following priorities guided data selection: (1) recent publication by the fluid manufacturer, (2) recent publication by another fluid manufacturer offering comparative information about several fluids, and (3) other published literature. Some data were unavailable

The data displayed were obtained using ASTM standard test methods; data from other test methods are not included, except in the case of MIDEL 7131. This synthetic ester fluid is used largely in Europe where IEC test methods are common; results from these methods are included where noted for MIDEL 7131. Although reference J names fluid types, not individual fluids, it was possible to identify individual fluids by comparing data in the reference to data published by individual fluid manufacturers.

Table D-1
Virgin Fluids—Data From Product Literature

Properties	Units	Test Method	Condition	Fluid Type											
				Mineral Oil		High-Temperature Hydrocarbon		Silicone		Synthetic Ester		Natural Ester			
				VOLTESSO 35		Beta Fluid®		XIAMETER® PMX-561		MIDEL® 7131		Envirotemp® FR3™		BIOTEMP®	
Physical															
Color	L	ASTM D1500		0.5	A	1.5	C	0.5	B	—		0.5	I	0.5	A
Visual appearance		ASTM D1524		—		clear & bright	B	crystal clear	D	—		clear, light green	I	clear & bright	N
Flash point	ºC	ASTM D92		150	A	272	C	300	D	260	F	330	H	340	J
Fire point	ºC	ASTM D92		180	A	308	B	370	D	322	L	360	H	360	J
Pour point	ºC	ASTM D97		-62	A	-24	B	-55	K	-60	G	-21	H	-20	J
Kinematic viscosity	cSt	ASTM D445	0 ºC	45	A	1950	C	90	K	280	L	180	L	276	J
			40 ºC	8	A	115	C	38	K	28	E	33	H	42	J
			100 ºC	2	A	12	B	16	K	6	L	8	H	9	J
Heat capacity (specific heat)	cal/gºC	ASTM D2766	25 ºC	0.43	L	0.45	M	0.36	M	—		0.45	H	0.57	J
Thermal conductivity	W/m K	ASTM D2717	25 ºC	0.14	L	0.15	C	0.15	D	—		0.17	L	0.17	J

Table D-1 (continued)
Virgin Fluids—Data From Product Literature

Properties	Units	Test Method	Condition	Fluid Type											
				Mineral Oil		High-Temperature Hydrocarbon		Silicone		Synthetic Ester		Natural Ester			
				VOLTESSO 35		Beta Fluid®		XIAMETER® PMX-561		MIDEL® 7131		Envirotemp® FR3™		BIOTEMP®	
Physical															
Relative density (specific gravity)	kg/m³	ASTM D1298	15 ºC	0.91	L	0.87	B	0.96	K	0.97	K	0.92	H	0.91	J
Coefficient of thermal expansion	volume/ºC	ASTM D1903	25–100 ºC	0.000730	L	0.000730	M	0.001040	M	0.000750	L	0.000740	L	0.000750	J
Electrical															
Dielectric breakdown voltage (minimum)	kV	ASTM D877		53	A	40	C	43	K	75 (IEC 60156)	E	56	H	52	K
Dielectric breakdown voltage (gap)	kV	ASTM D1816	1-mm gap	20	L	30	M	—		—		36	L	39	J
Dielectric Breakdown voltage (impulse)	kV	ASTM D3300		225	A	300	C	—		—		164	L	134	L
Dissipation (power) factor	%	ASTM D924	25 ºC,	0.05	L	0.01	C	0.0001	D	0.10	L	0.06	L	0.09	J
			100 ºC	0.07	A	0.10	B	—		—		1.85	L	0.19	J

Table D-1 (continued)
Virgin Fluids—Data From Product Literature

Properties	Units	Test Method	Condition	Fluid Type											
				Mineral Oil		High-Temperature Hydrocarbon		Silicone		Synthetic Ester		Natural Ester			
				VOLTESSO 35		Beta Fluid®		XIAMETER® PMX-561		MIDEL® 7131		Envirotemp® FR3™		BIOTEMP®	
Electrical															
Gassing tendency	µl/min	ASTM D2300		-4	A	20	C			positive	L	-81	L	-50	J
Volume resistivity	Ohm-cm	ASTM D1169	25 ºC	10^{15}	L	2.3×10^{13}	C	10^{14}	K	12×10^{12}	G	30×10^{12}	I	1.5×10^{13}	J
Relative permittivity (dielectric constant)	K	ASTM D924	25 ºC	2.2	L	2.3	C	2.7	D	3.2	G	3.2	L	3.1	J
Chemical															
Water content	ppm	ASTM D1533		20	A	15	C	30	D	50 (IEC 60814)	E	20	L	50	J
Oxidation stability	sludge, wt%	ASTM D2440	72 h @ 100 ºC	0.1	L	0.01	C	—		—		solid	L	—	
			164 h @ 110 ºC	0.01	A	0.06	C	—		—		—		—	
	neutralization (acid) number, mg KOH/g		72 h @ 100 ºC	0.3	L	0.14	C	—		—		—		—	
			164 h @ 110 ºC	0.01	A	0.26	C	—		—		—		—	
Neutralization (acid) number	mg KOH/g	ASTM D974		0.01	A	—		0.008	D	0.03	G	0.02	L	0.03	J

Table D-1 (continued)
Virgin Fluids—Data From Product Literature

Properties	Units	Test Method	Condition	Fluid Type											
				Mineral Oil		High-Temperature Hydrocarbon		Silicone		Synthetic Ester		Natural Ester			
				VOLTESSO 35		Beta Fluid®		XIAMETER® PMX-561		MIDEL® 7131		Envirotemp® FR3™		BIOTEMP®	
Chemical															
Interfacial tension	dynes/cm	ASTM D971	25 °C	49	A	45	C	—		—		24	L	26	L
Corrosive sulfur		ASTM D1275B		nil	A	nil	L	—		nil	E	nil	L	nil	L
PCB content	ppm	ASTM D4059		—		< 2		non-detectable	D	—		—		non-detectable	J
Environmental															
Biodegradability	%	CEC L-33-A-93	21 days	30	L	20	K	5	K	80	K	99	H	99	K

A Imperial Oil Limited, 2010. "VOLTESSO 35," Material Safety Data Sheet, Imperial Oil Limited, PO Box 2480, Station 'M', Calgary, Alberta T2P 3M9, Canada.

B DSI Ventures Inc., 2005–2009. "Beta Fluid," DSI Ventures Inc., 1320 E. Commerce St., Tyler, TX 75702-6125.

C DSI Ventures Inc., 2005–2009. "Insulating Oil Products Specification and Technical Guide," DSI Ventures Inc., 1320 E. Commerce St., Tyler, TX 75702-6125.

D Dow Corning Corporation, 2009. "XIAMETER® PMX-561 Transformer Liquid," Dow Corning Corporation, Corporate Center, PO Box 994, Midland, MI 48686-0994.

E M&I Materials Ltd, 2009. "MIDEL® 7131 Technical Datasheet No. 7," Environmental Behavior, M&I Materials Ltd, Hibernia Way, Trafford Way, Trafford Park, Manchester M32 0ZD, United Kingdom.

F M&I Materials, 2009. "MIDEL® 7131," Materials Safety Data Sheet, Technical Datasheet No. 10, M&I Materials Ltd, Hibernia Way, Trafford Way, Trafford Park, Manchester M32 0ZD, United Kingdom.

Table D-1 (continued)
Virgin Fluids—Data From Product Literature

G Wang, Z., 2009. "Use of Ester Based Insulating Fluids in Power Transformers," paper presented at CIGRE NGN UK Meeting, AREVA T&D, St. Leonards Avenue, Stafford, St17 4LX, Staffordshire, England, November 30.

H Cooper Power Systems, 2008. "Envirotran® Transformers: The Next Step in Advancing Safety, Value and Performance," Bulletin B100-98007, Cooper Power Systems, 1900 East North Street, Waukesha, WI 53188-3899.

I Cooper Power Systems, 2005. "Envirotemp® FR3™ Fluid," Product Information Bulletin 00092, Cooper Power Systems, 1900 East North Street, Waukesha, WI 53188-3899.

J ABB, Inc., 2009. "BIOTEMP®—ABB Sensible Solution: The Superior Biodegradable, High Fire Point Dielectric Insulating Fluid," Product Brochure, ABB Inc., 2135 Philpott Road, South Boston, VA 24592.

K Page, S.A., 2008. "Introduction to BIOTEMP®—ABB Sensible Solution," ABB Inc., 2135 Philpott Road, South Boston, VA 24592.

L ABB, Inc., 2008. "BIOTEMP® Biodegradable Dielectric Insulating Fluid for Distribution and Power Transformers: Available Technical Data & Further Test Plan Information," 2nd Edition, ABB Inc., 2135 Philpott Road, South Boston, VA 24592.

M Mendes, J.C., et al. 2007. "Oiled and Ready To Go: Advanced Application of ABB BIOTEMP® Vegetable Oil in a HV Power Transformer," ABB Review, ABB Inc., 2135 Philpott Road, South Boston, VA 24592.

N ABB, Inc., 2002. "BIOTEMP® Biodegradable Dielectric Insulating Fluid," Descriptive Bulletin 74-1050, ABB Inc., 2135 Philpott Road, South Boston, VA 24592.

E
VIRGIN FLUIDS—INDEPENDENT ENVIRONMENTAL TESTS

Table E-1 displays data from Environmental Technology Verification (ETV) and other independent tests describing the environmental properties of virgin transformer fluids. Some tests were omitted.

Fluid manufacturers specified performance limits for the products they submitted to California EPA for testing. Note that these limits may differ from the typical ASTM test values for fluid properties published in product literature (Appendix D).

Table E-1
Virgin Fluids—Independent Environmental Tests

Properties	Units	Test Method	Condition	Fluid Type							
				Mineral Oil	High-Temperature Hydrocarbon	Silicone	Synthetic Ester	Natural Ester			
				Brand Unknown	Beta Fluid®	XIAMETER® PMX-561	MIDEL® 7131	Envirotemp® FR3™ [A]		BIOTEMP® [B]	
							External Accredited Laboratory [E]	Cooper Power Systems	ETV Average [F]	ABB	ETV Average [F]
Environmental											
Aquatic Toxicity (LC_{50})	mg/l	EPA [G]		—	—	—	—	1000 [H]	250 juvenile; 317 adult	776 [H]	250
		OECD [I]		—	—	—	—	no deaths after 96 days	—	—	—
California Toxicity Criterion	mg/l			—	—	—	—	—	500 maximum		500 maximum

Table E-1 (continued)
Virgin Fluids—Independent Environmental Tests

Properties	Units	Test Method	Condition	Fluid Type							
				Mineral Oil	High-Temperature Hydrocarbon	Silicone	Synthetic Ester	Natural Ester			
				Brand Unknown	Beta Fluid®	XIAMETER® PMX-561	MIDEL® 7131	Envirotemp® FR3™		BIOTEMP®	
							External Accredited Laboratory[E]	Cooper Power Systems	ETV Average[F]	ABB	ETV Average[F]
Environmental											
Aquatic Biodegradability	%	CEC L-33-A-93[J]	21 days	—	—	—	—	—	—	97	99
		EPA Method OPPTS 835.3110[K]	28 days	—	—	—	—	99	120	—	—
		OECD 301B[L]	28 days	28[C]	—	—	—	—	—	—	—
		EPA Method 560/6/-82-003[M]	28 days	45.5[D]	—	—	—	—	—	—	—
		OECD 301F[N]	28 days	—	—	—	89	—	—	—	—

Table E-1 (continued)
Virgin Fluids—Independent Environmental Tests

[A] CalEPA, 2002a. *Environmental Technology Verification Report: Cooper Power Systems Envirotemp® FR3™ Vegetable Oil-Based Insulating Dielectric Fluid*, California Environmental Protection Agency, Department of Toxic Substances Control, Office of Pollution Prevention and Technology Development, Sacramento, California 94812-0806, DTSC R-02-02 (EPA 600/R-02/042), May.

[B] CalEPA, 2002b. *Environmental Technology Verification Report: ABB Inc. BIOTEMP® Vegetable Oil-Based Insulating Dielectric Fluid*, California Environmental Protection Agency, Department of Toxic Substances Control, Office of Pollution Prevention and Technology Development, Sacramento, California 94812-0806, DTSC R-02-03 (EPA 600/R-02/043), June.

[C] Conservation of Clean Air and Water-Europe (CONCAWE)

[D] U.S. Army Corps of Engineers USACE)

[E] M&I Materials Ltd, 2009. "MIDEL® 7131 Technical Datasheet No. 7," Environmental Behavior, M&I Materials Ltd, Hibernia Way, Trafford Way, Trafford Park, Manchester M32 0ZD, United Kingdom.

[F] Average of 3 samples

[G] Test procedures described in *Methods for Measuring the Acute Toxicity of Effluents and Receiving Waters to Freshwater and Marine Organisms* (EPA 1993)

[H] Single sample

[I] Organization of Economic Cooperation and Development (OECD) Test Guideline (TG) 203, "Fish Acute Toxicity Test" (OECD 2008)

[J] Coordinating European Council, "Biodegradability of Two-Stroke Cycle Outboard Engine Oils in Water"

[K] EPA Test Method OPPTS 835.3110, "Ready Biodegradability"

[L] OECD 301B, "Ready Biodegradability"

[M] EPA Test Method 560/6/-82-003, "Aerobic Aquatic Biodegradability"

[N] OECD 301F, "Ready Biodegradability"

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