Natural Ester Dielectric Liquids

by Lance R. Lewand
Doble Engineering Company

The newest versions of natural ester dielectric fluids have been in use in the electrical apparatus industry since approximately 1998 and are becoming more popular. Unlike transformer mineral oil, which is refined from petroleum derived from compressed plant and animal tissue (mostly microorganisms from 70 to 440 million years ago), these liquids are produced from renewable resources such as vegetable oils and seeds.

Reference is given to these liquids as "the newest version" because vegetable oils have been experimented with and used as dielectric liquids since the late 1880s. George Westinghouse and his team of engineers used castor oil and linseed oil as dielectric liquids and insulation impregnants. This helped to reduce the size of the transformers by reducing dielectric clearances and allowed the solid insulation to last longer by minimizing the effects of oxygen. Until Elihu Thomson patented mineral oil for use in transformers in 1892 and its acceptance in the mid-1890s, vegetable oils (natural esters) were the dielectric liquids used.

In fact, many vegetable oils have been tested over the years, including linseed, cod liver, hemp, walnut, poppy, sunflower, cottonseed, sesame, peanut, rapeseed, olive, and others. Two oils in particular, linseed and tung, were very important in the early years of transformer manufacturing. These oils were considered to be "drying oils" and, as such, polymerized easily when exposed to oxygen. Because of this characteristic they were used extensively in the formulation of insulating varnishes. [See Clark (1962).]

These same characteristics, however, presented problems and were objectionable when used as a liquid dielectric. Formation of organic peroxides occurred and eventually resulted in the formation of aldehydes and acids. These vegetable oils polymerized easily when exposed to oxygen. Such by-products are unwanted in transformer systems as they accelerate the degradation process of the liquid and solid insulation. In addition, vegetable oils have much higher viscosity and pour point characteristics and could not be manufactured consistently. Since early transformers were all free-breathing, oxygen played a major role. Thus, vegetable oils were quickly supplanted by the introduction of Western Pennsylvania paraffinic mineral oils which were in turn eventually succeeded by naphthenic-based mineral oils.

Beginning in the early 1990s, there was renewed interest in developing natural ester dielectric liquids able to overcome some of the deficiencies that plagued the vegetable oils used in the 1890s and 1900s. ABB Inc. and Cooper Power both began intensive research into the formulation of natural esters, and both now have commercially available products. In addition, Waverly Light and Power, a small city-owned utility in Iowa, has used a soy-based dielectric liquid developed by the University of Northern Iowa's Ag-Based Industrial Lubricants Research Program in pole top transformers since about 1998. This product is now produced by Cargill. Several patents were issued for these products beginning in 1999. [See Oomen and Claiborne (1999), McShane *et al* (2000), and Cannon and Honary (2000).]

The main purpose for development of many of these dielectric liquids was to create an environmentally friendly product that was not only stable when used as an insulating liquid in electrical apparatus but also readily biodegraded when exposed to the environment. This would allow spills and leaks to be handled more easily than transformer mineral oils. Since the first production and use of these liquids, other positive attributes have been discovered. As listed in

Lewand (2001), potential users of these types of dielectric liquids would expect some of the following qualities to be present.

- High level of biodegradability
- Nontoxic
- Material compatibility with electrical apparatus components
- Good dielectric strength and insulation properties
- Similar dielectric constant as the solid insulation
- Long-term oxidative and thermal stability
- Relatively low pour point
- Can be consistently produced
- Long service life
- Compatibility with presently used liquids (mineral oil, etc.)
- Reasonable cost

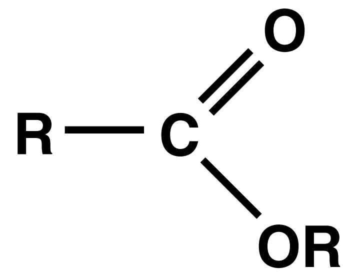
Examples of current, commercially-known, natural ester dielectrics are shown in Table 1.

Table 1 - Natural Ester Dielectric Liquids

NAME	TYPE	MANUFACTURER
BIOTEMP®	Comprised mostly of mono-unsaturated high oleic acid triglyceride vegetable oils. The oleic acid group is defined as having one carbon double bond, part of the eighteen carbon atoms in the hydrocarbon chain of a carboxylic acid. Examples of high oleic oils are sunflower, safflower, and rapeseed (canola).	ABB Inc.
BIOTRANS®	A mixture of partially hydrogenated soybean oil high in oleic acid content, methyl esters produced from soybeans, palm or coconut oils used to thin the dielectric liquid	Cargill
Envirotemp® FR3	Edible-seed oil based dielectric liquid. It is a natural ester (triglyceride - fatty acid ester) containing a mixture of saturated and unsaturated fatty acids with 14 to 22 carbon length chains containing one to three double bonds. Suitable vegetable oils, which may be used independently or combined, include: soya, sunflower, and rapeseed (canola).	Cooper Power Systems
Coconut Oil	Coconut Oil	University of Moratuwa, Sri Lanka

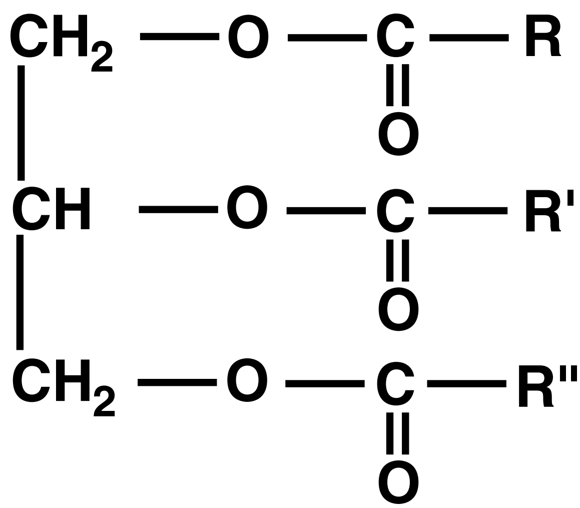
What is a Natural Ester?

Esters can be natural, such as those derived from vegetable oils as discussed in this article, or they can be made synthetically from a group of chemicals chosen to yield certain properties. "Ester" is a term applied to chemical compounds with a certain structure. The structure of a fatty ester is represented by the following formula:



The O represents oxygen, C represents carbon, R represents an alkyl or aryl group, OR' represents an alkyl or aryl group attached to an oxygen, a single dash represents a single bond, and a double dash represents a double bond. For those wishing to know even more chemistry, an alkyl group is one that contains carbon and hydrogen in the following pattern C_nH_{2n+1}. The n can be any number and simply refers to the length of the molecule. An alkyl group is derived from its alkane parent. An alkane is a hydrogen-to-carbon saturated compound in which all the groups attached to the carbon are single-bonded. An aryl group or aryl radical is an aromatic hydrocarbon in which there is one hydrogen less than its parent form.

All these ester oils have a triglyceride component of which many of the properties of the oil are based on the fatty acid content of the oil. A formula for a triglyceride is shown below.



The R, R′, and R″ are organic groups (carbon, hydrogen, oxygen) consisting of chains of eight to 22 carbons and are the fatty acid component. Fatty acids include oleic, linoleic and linolenic (unsaturated containing one to three double bonds), and palmitic and stearic (saturated fatty acids, no double bonds).

The type of bonding has a marked impact on the properties. For example, oils with multiple double bonds tend to oxidize more easily and potentially polymerize — not a quality wanted in a liquid dielectric in a transformer. Saturated fatty acids (single bond) offer better oxygen stability but also raise the pour point possibly to an unacceptable level such as 20 degrees Centigrade (68 degrees Fahrenheit). In countries like Sri Lanka this may not be a problem, but in the United States the ambient temperatures are often much lower. At temperatures below the pour point, the liquid turns into a solid and, thus, must function as a solid dielectric.

In some of the other natural ester dielectric liquids, a compromise was made where pour point considerations and oxidation stability were weighed against each other. For example, all three US-manufactured natural esters contain an oleic acid component which only has one double bond, allowing some oxygen stability and reducing the pour point to about -12 to -18 degrees Centigrade (10 to 0 degrees Fahrenheit) before the use of pour point depressants. It must be said that compromises are not only made in the refining of natural esters but also in transformer mineral oils as well. Not all properties are maximized since they may negatively influence other properties, and, thus, the refining process is based on meeting a specification with the refining equipment available at a cost a customer is willing to pay.

Refining of a Natural Ester Dielectric Liquid?

Natural esters are refined in a totally different manner than transformer mineral oils. The first major difference is the source of the material for refining. In the case of transformer mineral oils, crude oil is extracted from the ground by drilling and goes through a series of air and vacuum distillation steps, followed by treatment with hydrogen, pressure, and catalyst. In the case of natural esters, the source materials are crops that are grown and then harvested. In this respect, the seed oils are more attractive than mineral oils as they are a renewable resource.

Natural ester dielectrics are manufactured in multistep processes involving several techniques. Two techniques are used for obtaining the crude oil from oil seeds. Batch pressing is the first technique and has been used for some time. Batch processing consists of applying either hydraulic pressure to the vegetable seed or pulp via hydraulic press or through the use of a rotating screw or worm and is best suited for softer crops like sunflower and rapeseed. Another refining process involves crushing the seeds and extracting the oil with a solvent such a hexane and is better suited for harder crops such as soybeans.

A degumming step is necessary to remove materials other than oil, such as chlorophyll. This is performed either by physical separation, which takes time, or by combining the material with water and caustic material to accelerate the separation process.

The next step, a bleaching process that is part of a neutralization process, also subjects the oil to clay treatment to remove polar compounds. Deodorizing the oil is accomplished via steam distillation under vacuum up to 200 degrees Centigrade to remove unwanted volatile compounds. The last step, winterizing, which may be optional and depends on the starting material and the degree of refining, involves chilling the oil to remove excessive saturates.

Because these refining techniques can be carefully controlled, a more consistent product is produced. In addition, the new natural ester dielectrics differ from their predecessors not only in the refining process but also in the additives used. Whereas the early natural esters had no additives, the new ones have a variety of additives enhancing performance.

Additives

The natural ester dielectric liquids contain additive packages consisting of chemicals to reduce the pour point, aid in oxygen stability, and in some cases have an antimicrobial agent or copper deactivators. This is in contrast to mineral oil, which has either no additives or simply oxidation inhibitors. Mineral oil produced to Doble TOPS or ASTM D 3487 specifications are only allowed to contain DBPC (2,6-ditertiary-butyl paracresol, BHT) or DBP (2,6-ditertiary-butyl phenol) in concentrations up to 0.3 percent. DBPC and DBP have had a lengthy history of use in transformer oil and no adverse effects have been documented.

The U.S. patents for BIOTEMP®, BIOTRANS® and Envirotemp® FR3™ incorporate enough variation into the descriptions of each liquid that the exact combination and concentration cannot be determined. Most of these additives have been well-established in the chemical and food industries for some time, but it is not fully known if there are any adverse characteristics when used in transformers over a long period. The table below provides a listing of the additives and their described use. It must be emphasized that not all of these additives are used but the possibility for some or combination thereof to be used does exist. In some of the dielectric liquids listed in the table, the additive package can make up as much as three percent of the liquid.

Possible Additives in BIOTEMP®, BIOTRANS® and Envirotemp® FR3™

Liquid	Additive and Function
BIOTEMP	Oxidation Inhibitors: Phenolic antioxidants such as: BHA (butylated hydroxy anisole), TBHQ (mono-tertiary butyl hydroquinone), DBPC (BHT, 2,6-ditertiary-butyl paracresol/ butylated hydrotoluene), and aklyated diphenylamines Copper Deactivator: Benzotriazole derivative Pour Point Depressant: PMA (polymethacrylate)
BIOTRANS	Oxidation Inhibitors: citric acid (mostly used as sequester of metals to avoid catalytic effect of those metals), TBHQ (mono-tertiary butyl hydroquinone) Pour Point Depressant: diethylhexyl adipate, polyalkyl methacrylate
Envirotemp FR3	Oxidation Inhibitors: Phenolic antioxidants such as: BHA (butylated hydroxy anisole), TBHQ (mono-tertiary butyl hydroquinone), DBPC (BHT, 2,6-ditertiary-butyl paracresol/ butylated hydrotoluene), THBP (tetra hydro butro phenone) Pour Point Depressant: (polyvinyl acetate oligomers and polymers and/or acrylic oligomers and polymers) Antimicrobial agent: (BHA, potassium sorbate, sorbic acid, monoglycerides and/or Vitamin E)

Conclusions

Natural esters have been used as a dielectric liquid since the invention of the oil-filled transformer. Because of their chemistry these liquids have some limitations in their use. Recent advances in research and refining and additive packages have produced a new breed of natural esters that try to address these limitations. A later article will discuss the physical, chemical, and electrical properties of natural esters, differences as compared to transformer mineral oils, and some of the advantages of these oils.

References

Abeysundara, D.C., Weerakoon, C., Lucas, J.R., Gunatunga, K.A.I., and Obadage, K.C. “Coconut Oil as an Alternative to Transformer Oil,” in ERU Symposium, November, 2001.

Cannon, G.S., and Honary, L.A.T., “Soybean Based Transformer Oil and Transmission Line Fluid,” United States Patent 6,159,913, issued December 12, 2000.

Clark, Frank M. *Insulating Materials for Design and Engineering Practice*, John Wiley and Sons, New York, 1962, 1218 pages.

Lewand, Lance R. “Laboratory Evaluation of Several Synthetic and Agricultural-Based Dielectric Liquids” in *Proceedings of Sixty-Eighth Annual International Conference of Doble Clients*, 2001.

McShane, C. P., Corkran, J.L., Harthun, R.A., Gauger, G. A., Rapp, K.J. and Howells, E., “Vegetable Oil Based Dielectric Liquid,” United States Patent 6,037,537, issued March 14, 2000.

Oommen, T.V., and Claiborne, C.C., “Electrical Transformers Containing Electrical Insulation Fluids Comprising High Oleic Acid Oil Compositions,” United States Patent 5,949,017, issued September 7, 1999.

Lance Lewand received his Bachelor of Science degree from St. Mary’s College of Maryland in 1980. He has been employed by the Doble Engineering Company since 1992 and is currently the Laboratory Manager for the Doble Materials Laboratory and Product Manager for the DOMINO®. product line. Prior to his present position at Doble, he was Manager of the Transformer Fluid Test Laboratory and PCB and Oil Services at MET Electrical Testing in Baltimore, MD. Mr. Lewand is a member of ASTM Committee D 27.