As mailed to contributors 1/8

Section 2 Status

Table of Contents

		Page #
2.1	Introduction -- Askarel transformers and capacitors	1
2.1.1	Transformers	1
2.1.2	Capacitors	2
2.1.3	References	4
2.2	"Askarel-class" transformers	5
2.2.1	Description of the "askarel-class" of transformers	5
2.2.2	Sources and consequences of transformer tank rupture	5
2.2.3	Full-unit arc testing	13
2.2.4	Alternatives to askarels in "askarel-class" transformers	15
2.2.5	Test techniques and standards used by manufacturers to evaluate fluid-filled transformers	18
2.2.6	References	23
2.3	"Askarel-class" capacitors	24
2.3.1	Description of the "askarel-class" of capacitors	24
2.3.2	Probability and consequences of rupture	25
2.3.3	Full capacitor arc testing	26
2.3.4	Effect of alternative fluids on design and testing of the full capacitor unit	27
2.3.5	Test techniques and standards used by manufacturers and users to evaluate fluid-filled capacitors and cables	30
2.3.6	References	34
2.4	Dielectric and insulating fluids	35
2.4.1	Available fluids	35
2.4.2	Test techniques and standards by which fluid material properties are evaluated	51
2.4.3	Test techniques by which fluid flammability is evaluated	53
2.4.4	Test techniques by which toxicity is evaluated	62
2.4.5	Test techniques by which degradability is evaluated	62
2.4.6	References	63
2.5	The scope and influence of government regulations	66
2.5.1	Environmental regulations	66
2.5.2	Poisonous ingredients in foods	68
2.5.3	Occupational health	69
2.5.4	Transportation	72
2.6	The scope and influence of insurance and fire-code requirements	76

2.1 Introduction - Askarel transformers and capacitors

2.1.1 Transformers

Electrical transformers are used to change voltage, current and impedance levels in a wide variety of applications in electrical apparatus. These transformers range from the very smallest types in solid-state electronic circuitry to very large (1000MVA) 60-Hz power transformers. This study is concerned with the following restricted but important set of transformers:

1. "Network"-type distribution transformers, 500-2500 kVA, 12-34 kV, used in heavily concentrated urban and industrial load areas.
2. Precipitation transformers, high-voltage, for electrostatic precipitators which remove particulate pollutants from furnace exhaust gases.
3. Transformers for multiple-unit type electric railroad cars; these are located under the flat-bed of the car.

These are all liquid-insulated and operate at the commercial power frequency.

The liquid insulant has two duties, electrical insulation and cooling. Compared with air insulation, the liquid allows much closer spacing (smaller size) for a given voltage, and compared with air or solid insulation ("dry-type"), the circulating liquid coolant leads to a much smaller size for a given power rating. Mineral oil was traditionally used for this purpose and is still used for most power transformer applications. Estimates are that as much as 98% of all liquid-cooled power transformers use mineral oil, on an MVA or gallon-of-coolant basis.

The particular set of applications described above have critical non-flammability requirements, however, since they are generally located in heavily populated areas or are used in high-temperature or high fire-risk conditions. "Askarel" transformer liquid was developed, using blends of the polychlorinated biphenyls (PCB's), in the early 1930's to replace mineral oil in applications where non-flammability was an important requirement. The PCB's for these

MONS 047057

transformer askarels are manufactured by Monsanto Industrial Chemicals Company and are blended by Monsanto under the trade name "Aroclor." Two grades are used (showing percent chlorination and 1974 domestic sales in thousands of pounds.)

Aroclor 1242	(42%)	6207
Aroclor 1254	(54%)	6185

Ten to twenty percent of this production goes into precipitator and railroad transformers; most of the remainder is used in the "network" transformers. Approximately 5000 askarel-filled transformers are manufactured per year in the U. S., at a value of about $45 million.

While essentially all precipitator and railroad transformers are askarel-filled, only 10-15% of network transformers are the askarel-type.

2.1.2 Capacitors

As in the case of transformers, there is also a wide range in types and sizes of capacitors which are used in electrical apparatus. These are used for electric energy storage, tuning and power factor correction purposes. Their ratings can go from a few picofarads to many microfarads, with voltages from a few volts to over one-hundred kilovolts.

Although some high-frequency capacitors use air dielectric (air insulation), most capacitors are made up of multiple, thin layers of metal and solid insulation. To eliminate any weakening by the presence of air, these layer assemblies are then totally immersed in a liquid dielectric; often paper is used as one part of the solid insulator, and this paper is impregnated by the liquid. In addition to being a good electrical insulator, the liquid should have a high permittivity (dielectric constant, ε). The PCB's possess both of these features, and so grades of capacitor askarels have been used in capacitors since the introduction of the askarels in the 1930's. Whereas only a small percentage of transformers contain

askarel, nearly one-hundred percent of capacitors use this type of liquid insulant.

Because of the widespread use of PCB's in capacitors, Monsanto in 1971 introduced a more environmentally compatible formulation, Aroclor 1016, especially for capacitors. In 1974, Monsanto sold 21,955 thousand pounds of this fluid; the capacitor market for PCB's is considerably greater than the transformer PCB demand. The market value for PCB-insulated capacitors is in excess of $100 million per year.

Askarel capacitors are often divided into two categories, "power" and "industrial." The power capacitors are high voltage units which generally contain several gallons of fluid. They are used for power factor correction, which increases the efficiency of the electric power system. Without this efficiency improvement, approximately $1 billion in extra electric power plant and about 40M KWH in extra electric energy per year would be required to serve existing demand.

"Industrial" capacitors are generally smaller units which serve a large number of purposes including motor start and run, fluorescent light ballasts, arc welders, and power supply filters. The industrial class of capacitors is estimated to use one-half to two-thirds of the demand for capacitor askarel.

There is an important economic interdependence between the capacitor and transformer fluids markets which should not be overlooked in deciding on alternatives to PCB's. The capacitor and transformer askarels have different percentage contents of various PCB's, but they are both formulated from the same basic stock. They, therefore, aid each other in achieving the cost advantages of large scale production. Any shift of either market away from askarel would influence the price of the askarel to the other use. This factor should not be overlooked in evaluating the relative cost advantages of substitutes for PCB's.

MONS 047059

2.1.3 References, Section 2.1

Much of the material in this section was obtained through personal conversations with the manufacturers and users cited in the Introduction. In addition to these personal communications, the following sources were found to be helpful:

1. In Re: Proposed Toxic Pollutant Effluent Standards, (EPA); testimony on behalf of:
   a. General Electric Co., Mr. George D. Farnsworth, March 14, 1974.
   b. Westinghouse Electric Corp., Dr. James H. Wright, March 15, 1974.
2. Statement of Electronics Industries Association, to EPA, concerning Proposed Toxic Pollutant Effluent Standards, in a letter to the Honorable Russell Train, Administrator, June 25, 1975.
3. R. H. Munch, "New Capacitor Impregnants," IEEE, New York, Jan. 30, 1975.
4. L. L. Jackson, "Industrial Organic Chemicals vs. Alternative Dielectric Fluids, IEEE Power Engineering Society, Winter Meeting, New York, Jan. 1974, Paper No. C74 265-5.
5. "The Role of Polychlorinated Biphenyls in Electrical Equipment," General Electric Co., Schenectady, NY, Feb. 4, 1972.
6. "Study of the potential impacts of the proposed Toxic Substances Control Act, as illustrated by Senate Bill S. 776," for Manufacturing Chemists Association, Washington, DC, by Foster D. Snell, Inc., June 26, 1975.
7. National Conference on Polychlorinated Biphenyls, sponsored by Environmental Protection Agency, Chicago, IL, Nov. 19-21, 1975.

MONS 047060

2.2 "Askarel-class" transformers

2.2.1 Description of the "askarel-class" of transformers

The term "askarel" describes a broad class of fire-resistant,[1] Synthetic chlorinated hydrocarbon insulating liquids (polychlorinated biphenyls, "PCB's") which are used in certain special transformers, reactors and accessory electrical equipment where fire resistance is an important requirement. The askarel designation is used and defined more rigorously in the following standards and guidelines.

IEEE Std. 76-1974 IEEE Guide for Acceptance and Maintenance of Transformer Askarel in Equipment

ASTM D-2283-73 Chlorinated Aromatic Hydrocarbons (Askarels) for Transformers (also see D-2233-70)

National Electric Code, 1975; Art. 100 ("Definitions"), 450 (Transformers and Transformer Vaults), 460 (Capacitors).

Askarel is a fluid which is used both for insulation and for cooling. The transformer fluid must therefore exhibit proper electrical characteristics (particularly high breakdown strength[2] and low electrical loss) and good thermal qualities (adequate viscosity, specific heat, and thermal stability).

The transformer windings are completely immersed in the fluid, inside a tank which is sealed to prevent the fluid from escaping.[3] The tank must be heavy walled to withstand the sudden pressure of a high current electrical fault

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[1] "Fire resistant" materials are difficult to ignite, and when ignited burn at a slow rate. [2.2.1--see references at end of section]

[2] The high dielectric strength of the askarels in fact allowed a reduction in the size of the transformer, compared with mineral oil.

[3] The amount of askarel fluid in such a transformer ranges from 40 to 500 gallons, depending on the size and rating of the transformer.

MONS 047061

within the tank. The tank is generally finned for convective heat transfer to the surrounding air, and it often has a pressure relief valve to bleed off any small but steady rise of gas pressure within the tank (as from occasional low-level arcing or corona).

The fire-resistant character of this fluid, along with the high thermal stability and non-sludging qualities [2.2.2*], has made it an attractive transformer insulant since its introduction in 1932. Its high cost relative to mineral oil has, however, restricted its use to a fairly well defined set of applications which we will call the "askarel-class" of transformers. It is for this set of uses, then, that alternative transformer fluids are being offered, and test methods and standards for these alternative fluids should therefore be responsive to these specific applications.

The most important application of transformer askarel is in network transformers, which are essential components of the electric power distribution system in high load density urban areas. These transformers deliver the electrical power directly to large commercial buildings and so must be located in close proximity to the building, within, on, under or directly adjacent to the building. This close proximity to expensive, heavily-populated structures has led to the need for fire resistant electrical equipment, and askarel transformers are therefore specifically identified in the National Electric Code and in many local fire codes and ordinances. The same type of fire-resistant transformer, of course, finds wide use also in non-urban applications such as industrial plants, apartment buildings and shopping centers where the fire-resistant characteristic is equally desirable.

These transformers are generally in the 500 to 2000 KVA range, with primary voltages typically 12.8KV and secondary levels of 208V (three-phase, wye-connected). They are subject to high load and fault currents and so generally are fuse protected on their low voltage side. A fault developing within the

*References, shown in brackets, are listed at the end of each section.

MONS 047062

transformer tank itself will be cleared by the circuit-breakers at the substation.

Two other special uses for askarel transformers deserve mention. These are in electric railroad and mass transit traction equipment, and in electrostatic precipitation power supplies. The railroad application requires non-flammable equipment to prevent fire damage in case of accidents, but at the same time the electrical supply must be high-powered and compact, necessitating a liquid-cooled and insulated transformer.

Precipitators are used to remove particulate pollution from the flue gases in fossil-fueled electrical generating plants and other industrial furnace-type operations. The precipitator power supply and its power transformer must therefore be in close proximity to the furnace and the hot flue gas, and so again for fire protection purposes, askarel transformers are used. These two special uses are growing as mass transportation and air pollution control programs expand, and they now constitute ten to twenty percent of the askarel transformer demand.

It is evident from the above discussion that the "askarel-class" of transformers can equally well be called the "fire-resistant class" of transformers. Both external fires and fires from electric arcs internal to the transformer tank must be resisted. The askarels (polychlorinated biphenyls, PCB's) provide this resistance by generating hydrogen chloride which quenches any proximate flame. Their flash and fire points are also very high, making them difficult to ignite.

These askarel fluids and the hydrogen chloride which they generate are highly corrosive materials, and so extensive special designing and installation must be observed. Only particular, corrosion-resistant winding and tank coating materials can be used, "scavenger" materials must be present in the fluid to take up any small amounts of hydrogen chloride which are generated in normal operation, and in addition the transformer room or vault must be adequately ventilated to prevent buildup of HCl vapor.

Because of the toxicity and environmental problems of the PCB's, drains from askarel transformer installations must also be adequately filtered so that small or large scale spilling of fluid, during filling, testing, operation or catastrophic rupture, will be contained and not reach the ground water or navigable water systems.

These special requirements of existing askarel-transformer designs and installations are being identified in order to have a clearer picture of the processes which will be involved in replacing the PCB fluid with an alternative. Either the new fluid will have to be compatible with all of the characteristics of the existing askarel installation, or new installations will have to be designed to accomodate the new fluid. These constraints will shape the requirements of testing procedures to evaluate and qualify new fluids and transformers filled with new fluids.

2.2.2 Sources and consequences of transformer tank rupture

If mineral oil or a new liquid insulant such as silicone are to be used as replacements for askarel in transformers, one can be sure that containment of this fluid will be a prime objective, for safety, environmental and economic reasons. In anticipation of requirements for containment tests and standards, it will be the purpose of this section to review the present state of standards, tests and understanding in the area of transformer fluid containment.

Although the fluid is held in substantial drums or in the sealed transformer tank, loss of the fluid can still occasionally occur under several different circumstances:

a. During transport of the fluid or of the filled transformer,
b. During processing and handling of the fluid by the manufacturer or user,
c. During in-service operation of the transformer, and
d. Upon disposal at the end of the unit's life.

MONS 047064

Instructions for proper transport of the fluid and of the transformer are included within the general procedures of the Department of Transportation [Reference 2.2.3; see also Section 2.5]. In addition, the following are cited as examples of the types of guidelines and standards which could be developed to prevent leakage during acceptance, maintenance, handling and disposal of transformer and fluids:

a. "Guidelines for handling and disposal of capacitor and transformer grade askarels containing polychlorinated biphenyls," ANSI C107.1 - 1974; American National Standards Institute, 1430 Broadway, New York, NY 10018.

b. "IEEE guide for acceptance and maintenance of transformer askarel in equipment," IEEE Std 76 - 1974, Institute of Electrical and Electronic Engineers, 345 E. 47 St., New York, NY 10017.

These standards are discussed more fully in Section 2.2.5.

The oil spill regulations developed and enforced by the Environmental Protection Agency [2.2.4] also can serve as a model for judging the restrictions on other fluids leaking into the environment. These are discussed in Section 2.5.

A very rugged design is used for transformer tanks in order to maintain containment under most external or internal stresses. These tank designs are specified by industry standards published by ANSI [2.2.5]. Tank dimensions, static pressure withstand capability and corrosion resistance are specified. These standards should be reviewed for applicability with new fluids.

Rupture of a transformer tank while in service is most often due to arcing within the tank. This is a very complicated phenomenon which has been studied for many years. The following facts describe the phenomenon, its effects, and possible controls as presented in three recent articles by Barkan et. al. [2.2.6], Goodman and Zupon [2.2.7], Nettleton [2.2.8], and Ristuccia and Benton [2.2.9].

a. The arc most often starts as a low-current, high-impedance arc between adjacent turns somewhere within the transformer windings,

MONS 047065

b. A "high proportion" [2.2.7] of transformer failures result from the gradual build up of pressure in the tank due to the gas evolved by the low current arc. The pressure-relief valve present on most network transformers would avoid this as a cause of rupture in this important application of "askarel-class" transformers. Some users claim, however, that the pressure relief valve is more trouble than asset, and so avoid its use. A fuse should also be used to clear these low-level faults [2.2.6].

c. The high impedance arc will grow with time to a high current fault as the arc eats away the insulation on more turns. Because the use of pressure relief valves generally prevents the type of tank rupture described in part b. above, the high current arc may be the most prevalent cause of tank failure in the network transformers. We presume that the final growth of current is rapid, so that a bubble of high pressure gas forms within the fluid. The Barkan paper then shows that this bubble, as it expands, drives a "piston" of oil against the tank wall, momentarily overloading the wall and causing rupture.

d. Techniques for calculating the peak tank wall pressure under arcing faults are presented in both the Nettleton [2.2.8] and the Barkan [2.2.6] articles, but both also point out the difficulty of this for actual tank geometries. The static pressure relief valve is of no use here because of the rapid rate of pressure rise [2.2.9], and gas-flame venting techniques are also generally inapplicable for the same reason [2.2.8]. There is apparently a proposed revision to the ANSI transformer standard (C57.12.20-1971) for a standard transformer arc test to determine the necessary tank arc pressure withstand capability [2.2.9].

e. Further complicating the pressure calculation are the effects of energy release by burning of the fluid and of fluid products. This energy will build up the pressure, and the pressure wave will have characteristics due to being flame - as well as arc-driven [2.2.8].

f. One should not rely purely on tank withstand strength to prevent tank rupture under arcing; but rather this should be coordinated with a properly specified current-limiting fuse [2.2.6, 2.2.9]. The peculiar impedance characteristics of the arc prevent use of familiar I^2t types of fuse specifications; rather, the fuse manufacturers should recommend the proper fuse, based on the user's known voltage and fault-current levels.

Protection against the high current arc is of great importance, not only because it may be the most prevalent source of "askarel-class" transformer failures, but also because the arc is a high-temperature source which can ignite the fluid or the decomposition products due to the arc. Thus, protective tests and standards must coordinate the available temperature and energy (as for instance determined by a current limiting fuse) with the ignition temperature and energy of the fluid and of flammable components created by the arc. The "full unit arc testing" discussed in the next section (Section 2.2.3) will explore this type of testing in depth.

It is worth noting at this point that an arc in an insulation fluid can cause a wide range of decomposition products, depending on the chemical nature of the fluid, the availability of reactant gases such as oxygen and nitrogen, and the intensity (temperature) of the arc. Products can be flammable, explosive, corrosive and toxic. As examples, arcs (or low level discharges such as corona) can decompose mineral oil into hydrogen and hydrocarbon gases (and probably water), while askarels are said to break down to hydrogen chloride, nitrogen, carbon monoxide, carbon dioxide, and oxygen [2.2.10].

Not only can these products be directly harmful, but they can also weaken the dielectric strength of the insulating fluid and thereby set the stage for subsequent high current flashover and tank rupture. One should, therefore, seek standard procedures by which the fluid can be cleaned up at regular intervals, or after known arcing, in order to avoid future equipment failure. As guides in preparing such standards, we should note the following procedures which are now regularly employed.

a. "Scavenger" substances are mixed with askarels to take up the corrosive hydrogen chloride which is produced by occasional low level electrical discharges within the fluid.

b. In spite of the presence of scavenger material, users are instructed to bubble nitrogen through the fluid immediately after known arcing in order to pick up hydrogen chloride before it can do corrosion damage.

c. The IEEE standard 76-1974 suggests that moisture content and dielectric strength of askarel be regularly checked if arcing is known to be occuring.

Because of the combination of preventive measures outlined above, manufacturers and users report that present transformers of the network type experience about a .01 to .02% yearly rate of tank rupturing failures. Tests, standards, and guidelines must be prepared for new fluids in order that low failure rates will also be obtained for new transformer fluids.

Even though a low rupture rate is experienced with transformers, it is still industry practice, generally backed by fire or environmental code enforcements, to place fluid-insulation transformers in vaults. Mineral oil units must be in fire-proof vaults [2.2.11]; askarel transformer vaults need not be fire-proof but must have adequate ventilation and drainage facilities so that spilled fluid is contained and toxic vapors do not accumulate [2.2.12].

2.2.3 Full-Unit Arc Testing

In the early days of askarel usage a short-circuit test and an arcing test were performed by Underwriters' Laboratories, Inc. on actual transformers filled with an askarel (General Electric "Pyranol"). Details of these tests are reported in the ULHH No. 2581 Report, dated September 29, 1934. More recently, catastrophic explosion (arc) tests with several insulating fluids were performed by RTE Corporation [2.2.13]

1. Underwriters' Laboratories Tests

The transformers were rated 60 cycles, 5KVA, 2200-110 volts. One of these was short-circuited externally. The other was subjected to an arcing test by being connected to a 12,000 KVA generator so as to apply 7,500 volts between the ungrounded 122-volt lead and ground. In both cases, pressure-tight covers were provided with pressure-relief diaphragms designed to rupture at not less than 10-12 psig.

The results of the two tests were rather similar: no appreciable change in pressure was noted for approximately 2 minutes after current was supplied to the transformer. Thereafter, the pressure increased rather rapidly until the diaphragms ruptured. Large volumes of gases were liberated during the tests, but the gases did not ignite upon application of a test flame.

2. RTE Arc Tests

Four insulating fluids were tested: mineral oil, Silicone DC-200 (Dow Corning), RTEMP (RTE Corporation), and an askarel (Westinghouse Inerteen 70-30). Approximately four gallons of each fluid were used, preheated to 150°C.

The containers were sealed before the test, but the rupture pressure (presumably roughly the same in all four cases) was not specified. In each test the liquids were subjected to a massive arc discharge: 4660 to 4820 amps at

4800 volt open circuit. All four samples showed a violent flash initially, with rupture of the container lid and wide spraying of liquids, but only mineral oil continued to burn. It is important to note that mineral oils used in transformers have flash points in the vicinity of 150°C (146°C minimum according to standard specifications) and fire points about 15°C higher. Askarels, on the other hand, have no true flash point (so-called pseudo flash points do occur), and no fire point up to the boiling point. Silicone oils have very high flash points (about 300°C)--see the section on flammability tests. RTEMP, being a high hydrocarbon fraction, presumably also has a high flash point. Thus the tests were conducted with initial fluid temperature near the flash and fire points of mineral oil, but substantially below flash points of other fluids.

3. Reaction from Industry and Insurance

The consensus appears to be that both sets of tests (UL and RTE) show askarels to have very low flammability. The UL rating of 2-3 on the scale of 100 for flammable fluids reflects this consensus. Furthermore, the Factory Mutual representatives appear satisfied that the RTE tests show also the silicone fluids and RTEMP to have flammabilities in the same, generally acceptable, range as askarels. UL representatives have not commented on the RTE tests.

On the other hand, the nature of the initial flash in RTE tests and of the observed pseudo flashes in flash point testing of askarels does not appear to be understood, so some concern remains. Intense heating of the decomposition products by the arc may lead to some reaction of these products with air. Contributors have also suggested that in arc explosion tests of askarels the fluid is electrically heated to decomposition temperatures, and that decomposition itself is exothermic. As a result, several representatives from industry and insurance business have commented that a carefully standardized arcing test should be developed. Manufacturers, users, and testing laboratory personnel have indicated a willingness to cooperate in developing such a test.

2.2.4 Alternatives to askarels in "askarel-class" transformers; influence on total transformer tests and standards

We must emphasize again that the purpose of this study is not to evaluate alternatives to askarels but rather to survey the status of tests and standards by which such alternatives may be judged. The characteristics of the available alternatives must be explored, however, to the extent that unique characteristics will influence the definitions of tests and standards. This section will emphasize the effect of alternatives on the total unit, while the next section will look at standards for the fluids themselves. Many concepts originally brought up in Section 2.2.2 ("Sources and consequences of transformer tank rupture") will be revisited in terms of the goals of this section.

The characteristics of available alternative fluids are presented in detail in Section 2.4 and so need not be repeated here. It is important to note, however, that these represent a wide range of density, viscosity, operating temperature, corrosiveness, volatility, hydrolytic stability, flammability, etc. Because of the diversiveness of these values, we will see that universal performance specifications will be difficult to write without taking into account the unique characteristics of each particular insulant. This will be equally true in establishing universal performance standards for the total transformer assembly. The important fluid characteristics which must be accounted for in any future transformer standards and specifications are listed below:

a. Material compatibility. The chemical activities of the available insulation fluids differ in kind and degree. Tests must, therefore, be devised to measure adequacy of the materials used for protective coating on inside of the tank walls, for insulation on the wire used for the transformer windings, and for miscellaneous other components such as disconnects and fuses which might be in contact with the fluid.

b. Temperature. If the particular insulating fluid requires an unusually high operating temperature, all materials used to construct the transformer must be compatible with this temperature, and in addition the location of the operating transformer must be selected to be acceptable to this higher operating temperature. Existing standards such as:

"General Principles for Temperature Limits in the Rating of Electric Equipment," IEEE Std 1-1969

are probably adequate for this purpose. Standard sampling techniques may also be desired to insure the stability of the fluids at high operating temperatures.

c. Cooling. The fluid in a transformer is used as both an insulating and cooling medium. An economically competitive transformer must have its cooling system design closely matched to the characteristics of the coolant fluid, and so new fluids will undoubtedly require some redesign of the transformer. This may necessitate new standards on transformer tanks, cooling surfaces, circulating equipment, etc., and the user may demand more thorough cooling specifications on transformers with new coolant fluids.

d. Hydrolytic stability. Water is generally a problem in transformer fluid, but the degree of difficulty will probably change from one fluid to another. Sealing against moisture entry, and processes for removal of water should, therefore, be specified for each new insulant.

e. Containment. The different fluids will have different densities and required volumes for any given kVA and kV class of transformer, so space and supporting structure specifications must be made up for each new fluid. The types of seals will also have to be correlated with

each fluid, since difference fluids have difference leakage characteristics. Since rigorous containment of any fluid may be the goal of future regulations, standards and tests for evaluating containment of each tank/fluid combination will be of increasing importance.

Standards for external protection should be coordinated with the particular class of transformers, the fluid and the level of tank containment security. By external protection, we mean secondary protection provisions, beyond the tank -itself. This includes both vaults, for extra containment in case of tank failure and protective circuit elements (such as circuit breakers and fuses) to prevent tank rupturing arcs from occurring. Much as an electrical system has its various power and protective elements coordinated with one another, so also might the industry consider more quantitative coordination of the levels of transformer containment. One might, for instance, consider that increased speed and redundancy of circuit breaker and fuse protections could allow a less cumbersome and expansive vault structure. Extensive probability analyses of actual operating experience would be required before such a coordination plan could be acceptable for fire codes and insurance purposes.

Although no new standards or tests may be required, we include, for completeness, a mention of two other available alternatives, namely dry-type and gas-cooled transformers. These transformers depend on ambient air or special gas insulation. The dry types are available now and are being used extensively in place of askarel transformers. Relative reliability and overload capability have been questioned by some users but are quite acceptable to others, which may mean that standardized tests on these characteristics should be available to clear up such disagreements.

Gas cooled transformers are not yet as readily available for substitution. Tests may be required to establish the harmlessness or the need for containing

MONS 047073

products of arcing within the insulation gas. Development of these tests should be guided by the extensive existing work on entire gas-insulated substations.

2.2.5 Test techniques and standards used by manufacturers and users to evaluate fluid filled transformers

The transformer manufacturer and user have the following standards documents available for guidance in selecting and handling the insulating fluid.

1. ASTM D 2283-74 "Standard Specification for Chlorinated Aromatic Hydrocarbons (Askarels) for Transformers."
   This document gives detailed specifications of the physical, chemical and electrical properties of six askarels which have, or are being used in transformers and identifies specific test methods.
2. ASTM D 3146-75 "Standard Specification for Oxidation - Inhibited Mineral Insulating Oil for Use in Transformers and Circuit Breakers."
   This document gives detailed specifications of the physical, chemical and electrical properties of the oil together with approved test methods.
3. ASTM D 1040-73 "Standard Specification for Uninhibited Mineral Insulating Oil for Use in Transformers and in Oil Circuit Breakers."
   This document gives detailed specifications of the physical, chemical and electrical properties of the oil together with approved test methods.
4. ANSI C 59.131-1971 "Guide for Acceptance and Maintenance of Insulating Oil in Equipment" [Also issued as IEEE (Institute of Electrical and Electronics Engineers) Std. 64-1969.]
   The purpose of this Guide is to assist in evaluating the serviceability of oil received in equipment; oil as received from the refiner for filling new equipment at the installation site, and as processed into such equipment. It also is intended to assist the operator in maintaining his oil in serviceable condition. The Guide recommends standard oil

tests and evaluation procedures, methods of reconditioning and reclaiming, the levels at which these become necessary, and the routines for restoring oxidation resistance where required by the addition of inhibitors.

5. IEEE Std. 76-1974 "Guide for Acceptance and Maintenance of Transformer Askarel in Equipment."

   This guide assists in evaluating askarel as received in transformers, reactors, and accessory equipment operated at power frequencies and in efforts to maintain askarel in serviceable condition. It recommends standardized tests and evaluation procedures. Methods are outlines for reconditioning and reclaiming askarel whenever necessary.

6. ANSI (American National Standards Institute) C 107.1-1974. "Guidelines for Handling and Disposal of Capacitor- and Transformer-Grade Askarels Containing Polychlorinated Biphenyls."

   This document gives typical physical, chemical and electrical properties of askarels used in insulating fluids in transformer construction, details methods of shipping and handling, spells out necessary safety precautions, recommends labeling practices and details approved disposal techniques. It also lists organizations having facilities for analysis and for disposal and details an analytical procedure for the determination of airborne PCB's.

7. IEEE Draft "Specification for New, Unused Transformer-type Askarels."

   This specification covers bulk shipment in tank cars and drums of new, synthetic, nonflammable electrical insulating liquids of the chlorinated aromatic type known as askarels which are used as insulating and cooling media in liquid-filled transformers. While this specification is intended to cover the composition and characteristics of askarels for purchase only and does not apply to liquids in apparatus, a number of discontinued types are included for purposes of identification and historical significance.

MONS 047075

8. IEEE Std. 283-1968 "Guide for Installation of Oil-Immersed Distribution Transformers."

   This document suggests procedures to be followed in filling with oil those large transformers which are customarily shipped to the point of installation without the oil.

9. A NEMA Standards Document titled "Proposal for American National Standards on Mineral Insulating Oil for Use in Electrical Apparatus" is in the final stages of preparation. It is intended "to provide a functional industry standard that will assure a continuing supply of a single mineral insulating oil that adequately meets the needs of equipment manufacturers and oil refiners." It sets functional limits for the essential physical, electrical, and chemical properties and specifies the ASTM test methods to be used. Presumably it will ultimately replace items 2 and 3 above.

10. Federal Specification VV-I-530a "Insulating Oil, Electrical (For Transformers, Switches and Circuit Breakers." This standard specifies the physical properties required, establishes quality assurance provisions, and gives instructions for testing. It identifies several ASTM documents as forming a part of the specification.

11. Federal Specification VV-I-1219 "Insulating Fluid, Electrical (Noncombustible)"

    This standard applies to "liquid of the chlorinated aromatic hydrocarbon type (askarels) with coverage similar to that of VV-I-530a.

The following standards relate to the specification and performance of the transformer itself:

1. ANSI C57.12.00-1973 (also IEEE #462) "General Requirements for Distribution, Power, and Regulating Transformers."

This standard specifies (1) service conditions; (2) preferred ratings; (3) insulation classes and dielectric tests; (4) tolerances on losses, impedance, ratio, regulation and temperature rise; (5) tests; (6) such construction details as bushing class, marking of terminals, nameplate data, etc.; and (7) short circuit characteristics.

2. ANSI C57.12.90 (also IEEE #262) "Test Code for Distribution, Power, and Regulating Transformers."

   This standard prescribes methods for performing the tests specified in C57.12.00-1973 (above) and in the separate transformer standards of the C57.12 series. The test methods covered are: (1) resistance measurements; (2) dielectric insulation; (3) losses and impedance; (4) ratio and regulation; (5) temperature rise; (6) insulation power factor; (7) polarity and phase relation; and (8) short circuit calculations. C57.98, an Appendix to C57.12.90, covers impulse tests.

3. C57.12.90a-1974 (also IEEE #262A) (Draft Standard) "Distribution and Power Transformer Short-Circuit Test Code."

   This code defines a procedure by which the mechanical capability of a transformer to withstand short-circuit stresses may be demonstrated.

Other standards and guides in the ANSI C57 series (there are about 30) include such documents as:

C57.12.20-1974 "Requirements for Overhead-Type Distribution Transformers 67,000 Volts and Below"

C57.12.21-1969 "Requirements for Pad-mounted Compartmental-Type Single-Phase Distribution Transformers"

C57.12.40-1967 "Secondary Network Transformers, Subway and Vault Type (Liquid Immersed)"

C57.100-1974 "Thermal Evaluation of Oil-Immersed Distribution Transformers"

C57.93 (also NEMA TR-5-1956) "Guide for the Installation and Maintenance of Oil-Immersed Transformers"

C57.92 "Guide for Loading Oil-Immersed Distribution and Power Transformers"

4. NEMA TR1-1974 "Transformers, Regulators and Reactors"

   This document identifies the ANSI transformer standards which have been approved as NEMA standards and includes more detailed specifications regarding such characteristics as audible sound levels, external clearances between live parts, accessories, and some test procedures.

5. NEMA TR11-1967 "Small Power Transformers with 65C Average Winding Rise and Distribution Characteristics."

   This covers electrical characteristics and mechanical features of this class of transformers.

The above are representative of about ten NEMA standards dealing with various classes of transformers.

6. UL (Underwriters Laboratories) 506 "Specialty Transformers"

   This standard covers requirements for air-cooled transformers and reactors for general use but does not cover oil-filled units.

7. AAR (Association of American Railroads) SM262 "Specifications for Impulse Transformer for Coded Systems Control"

8. AAR SM165 "Specifications for Transformer, Oil-Immersed, Self-Cooled"

9. FM (Factory Mutual) 5-27 "Fire Prevention Transformers"

10. FM 5-275 "Arc-Furnace Transformers"

11. FM 14-8 "Inspection and Maintenance of Transformers"

(Note: Items 7-11 above are not in hand and thus no further description is available.)

Section 2.4.2 should be consulted for designation of the standards and techniques used for specifying and measuring the various fluid material properties identified in the above transformer standards.

2.2.6 References, Section 2.2

Much of the material in this section was obtained through personal conversations with the manufacturers and users cited in the introduction. In addition, the following articles are referenced in the text:

2.2.1 "Transformer askarel inspection and maintenance guide," Monsanto Company Bulletin No. IC/FF-38R, revised March, 1975.

2.2.2 R. N. Sillars, Electrical Insulating Materials, IEE Monograph 14, 1973; Section 10.2.1.

2.2.3 49CFR 100-199, revised October 1, 1974.

2.2.4 "Oil Pollution Prevention," Environmental Protection Agency, 38FR 34164, December 11, 1973.

2.2.5 C57.12.40; American National Standards Institute.

2.2.6. P. Barkan, et. al., "Overpressure phenomena in distribution transformers with low impedance faults: experiment and theory," F 75 464-8, IEEE PES Summer Meeting, San Francisco, July 1975.

2.2.7 E. A. Goodman, L. Zupon, discussion to Barkan paper (F 75 464-8).

2.2.8 M. A. Nettleton, "Explosions due to faults in electrical equipment," Electrical Review, 25 July 1975, pp. 116-119.

2.2.9 D. J. Ristuccia, R. E. Benton, "Ten most-asked questions on violent transformer failure," Transmission and Distribution, January, 1975, pp. 30-31.

2.2.10 A. E. Knowlton, editor-in-chief, Standard Handbook for Electrical Engineers, Ninth Edition, McGraw-Hill Book Co., New York, 1957, 4-561, 4-570.

2.2.11 National Electric Code, 1975; Sec. 450-24, "Oil-insulated Transformers installed indoors," NFPA, Boston, (also see Ref. 2.2.8, Sections 15-102, 4-572, 14-300).

2.2.12 National Electric Code, 1975; Sec. 450-23, "Askarel-insulated transformers installed indoors," NFPA, Boston.

2.2.13 D. A. Duckett, "Catastrophic explosion tests in insulating fluids," RTE Corporation, Wankesha, WI 53186, November 9, 1974.

MONS 047079

2.3 "Askarel-class" capacitors

2.3.1 Description of the "askarel-class" of capacitors

In Section 2.1.2, descriptions were given of the important uses of askarel-impregnated capacitors, namely "large" ones for power factor correction on electric power systems and "small" industrial ones for fluorescent tube ballasts and for motor starting. These are generally constructed by winding alternate sheets of metal foil and paper and/or film dielectric in round or flattened rolls. One or more of these rolls are connected together inside a closed metal housing which is then filled with the askarel.

The paper dielectric material has a high permittivity (ε_r~8), but it is dried before assembly into the capacitor, and it contains a large volume percentage of open air space. The askarel impregnates the paper, filling the air space voids. Askarel is uniquely suited to this dielectric application because its high permittivity (ε_r~5) reasonably matches the paper, and therefore causes less nonuniformity in electrical stress. The net high permittivity and the high dielectric strength of askarel also allow for a smaller capacitor per KVA or Kilojoule rating.

This combination of high dielectric constant (permittivity) and high dielectric strength would be sufficient to make askarel a favorable impregnant for capacitors. Its stability and nonflammability are additional characteristics which capacitor users have come to accept and depend upon through the many years that askarel has been essentially the exclusive capacitor impregnant. The comment is occasionally made that capacitors, particularly the large power factor correction types, are generally out-of-doors or in vaults and so flammability is not an issue as with transformer fluids. But this is definitely a minority viewpoint, and the majority of manufacturers and users indicate that they depend on

the nonflammability of askarel capacitors. More will be said about this flammability issue in Section 2.3.3.

In considering test techniques for alternate capacitor fluids, then, we can at this time identify the following factors: dielectric constant (permittivity, ε), dielectric strength, impregnability, flammability, and stability. Toxicity, environmental degradability and compatibility with other capacitor materials will also be added to the list in subsequent sections.

2.3.2 Probability and consequences of rupture

The rate at which the small industrial capacitors experience a tank-rupturing failure is very low; and when one of these small capacitors fails, there is little loss of fluid.* The total amount of fluid in all small industrial capacitors is, however, large, as shown in Section 2.1.

In the case of the larger, power-type of capacitor, again failure rate is low; the tank-rupturing type of failure is estimated to occur to .1% or less of the capacitors in service per year. Generally, a capacitor will fail by an internal arc short-circuiting the unit. Each power capacitor is generally individually protected by a current-limiting fuse, and this fuse will blow when the capacitor fails, leaving the capacitor-fuse unit open-circuited.

Often, power capacitors are used in parallel-series connected groups, or banks, and upon failure of one capacitor in the bank, all parallel capacitors will try to discharge through the failed unit. The current-limiting fuse limits this "in rush" current so that the other capacitors in the bank are not damaged.

NEMA standards** exist for identifying the proper fuse to use to protect any given capacitor. These are somewhat out of date, however, so a manufacturer

*In a capacitor containing paper insulation, 80% of the fluid is absorbed and so will not spill out even if the can does rupture.

**CP 1-1971, "Shunt Capacitors," National Electrical Manufacturers Association, New York. See also ANSI C55.1-1968 (IEEE No. 18), "Shunt Power Capacitors."

MONS 047081

will generally provide the necessary information for his capacitors. There is need, therefore, for a newly-created set of industry-wide standards for protection of new capacitor designs with new types of impregnant dielectric fluids.

2.3.3 Full capacitor arc testing

We have established in Section 2.2 that flammability is an important characteristic of "askarel-class" transformers and that the insulating fluid has been in the past and should continue to be qualified by full transformer arc testing. We have also recognized the importance of nonflammability of capacitors, but it must be reported that there is little documented experience or interest in arc or flame testing of capacitors.

The apparent justifications for this lack of testing are the low rate of capacitor failure and the small amount of fluid in any one capacitor. Fuse protection as described in Section 2.3.2 also reduces concern for rupture and fire.

In evaluating the need for full unit flammability testing of capacitors, one should also keep in mind the following factors:

a. New capacitor dielectric fluids generally are more flammable than askarels.

b. The paper and film, which make up a large percentage of the bulk material within a capacitor, are generally flammable.

c. Power factor correction capacitors are generally used not singly but rather in large multiple-unit banks. The flame from a single unit might be unconsequential, but it could lead to a dangerous, full-bank fire.

d. Use of many capacitors in large, closely spaced banks also has another risk. Unless each capacitor is properly fused, all parallel branches of a bank can discharge through a single unit which develops an internal, short-circuit fault. The sudden release of this large stored energy might lead to significant damage and fire.

MONS 047082

Manufacturers of fluids and capacitors have privately run occasional arc tests on capacitors to study flammability effects after a bank-rupturing fault. No definitely recommended format for such testing has been brought to our attention, however, and the indication is that considerable design and testing would be required before a quantitatively interpretable and repeatable test could be devised. Several parties involved in the manufacture and use of capacitors did feel rather strongly that such a test should be developed, however, particularly in light of the increased flammability of the new fluids.

2.3.4 Effect of alternative fluids on design and testing of the full capacitor unit.

The dielectric fluid must be compatible with all other materials with which the fluid makes contact inside the capacitor casing. As in the transformer situation, the inside coating of the metal capacitor tank must be non-reactive with the fluid. Since the fluid permeates directly to the metal foil electrodes, either the metal and fluid must be compatible or the metal must be treated with a protective coating.

In capacitors, the most serious material coordination problem is between the fluid and the insulating sheets which separate the foil electrodes. If this is a paper, then the fluid must be able to completely impregnate the paper, leaving no voids in which corona discharges can be initiated. Although certain fluid characteristics such as molecular weight and viscosity will help to screen out obviously improper fluids, adequacy of impregnation is best evaluated finally by testing the impregnant fluid in a true film-electrode capacitor geometry. One should be on the watch not only for immediate corona from inadequate impregnation, but also for weakening of the dielectric strength of the fluid, which can result from the fluid dissolving impurities out of the solid insulation material.

MONS 047083

incompatibility of a new fluid with the existing film and paper may be solved by going to new paper and film rather than by rejecting the new fluid. Thus, tests must be devised so that combinations of fluid and solid films can be evaluated on a controllable and comparative basis, and criteria for interpreting these tests must be devised so that new fluids are not rejected merely because of inadequacies in the paper or film. The best practical combinations of fluid and solid must be compared.

In the previous paragraph, we sought the best combination of impregnant and paper from a materials compatibility standpoint. It is important, however, to also coordinate dielectric characteristics. Severely mismatched dielectric constants will cause very uneven electric stress which can lead to corona and flashover in the more highly stressed member. Thus, askarel was a good fluid to use with paper since both have relatively high dielectric constants. The plastic films which are now in use in capacitors, such as polypropylene, have lower dielectric constants and so lower ε fluids can be used.

Using lower dielectric constant materials means that the capacitance per unit area of electrode is less for a given electrode separation, larger area (larger capacitor size) is needed for a given capacitance, and larger voltage or size are needed for the same energy storage. Regardless of what material is selected, its dielectric constant should be accurately known under actual operating conditions, and so its ε should be measured with the material in the true operating electric field. This may suggest that an extension be made in the ASTM standard test for dielectric constant (D924).

The size of the capacitor is influenced not only by the fluid dielectric constant, for a given capacitance, but also by the dielectric strength, for a given voltage. Decreased capacitance and energy storage because of decreased dielectric constant can potentially be regained by higher dielectric strength

MONS 047084

materials which allow higher fields and voltages. The design of the capacitor is, therefore, influenced by the dielectric strength (breakdown strength) of the fluid. The breakdown strength of the fluid itself may be measured by standard test procedures, as described in Section 2.4.2. Final capacitor designs, and test capacitor geometries can be evaluated by methods outlined in Section 2.3.5.

The maximum operating voltage of a capacitor is generally set by its corona inception and extinction levels, rather than by the flashover voltage. The low current, but continuous corona discharge causes damage to solid and liquid dielectric material and therefore leads to short life and failure of capacitors even though the operating voltage may be well below the breakdown level. Detection and measurement of corona and particularly of its inception extinction points are therefore extremely important in order to specify the maximum safe voltage for long life. These corona levels are not characteristic of just the insulating fluid, itself, however, but rather of the fluid in the actual electrode configuration, including the electrode material, the microscopic surface conditions, and purity of the electrode/fluid interface. An absolute measure of corona inception for a pure, isolated fluid is therefore of little value, and one must instead determine the inception level for the whole electrode/insulator configuration, assembled according to routines which would be followed in manufacture. Corona measurement techniques are specifed in ASTM D 1868-73.

In addition to corona, losses in capacitors result from resistive and dielectric properties of the fluid. These can generally be evaluated for the pure, isolated liquid as described in Section 2.4.2. The measurement should duplicate operating conditions (frequency, temperature, electric field) as closely as possible. Generally, higher dielectric constant materials exhibit higher loss, because of the large and rapid molecular polarization changes required by high permittivity materials in a-c fields.

A final important characteristic of the capacitor dielectric fluid is its stability. It must show little change in dielectric, chemical or physical characteristics under actual electrical and thermal operating conditions over the many years expected life time of the capacitors. Frequent comments from fluids manufacturers, capacitor manufacturers and users brought out (1) the importance of this characteristic, (2) the difficulty in defining and measuring stability, and (3) the importance of the measurement being in as realistic an environment as possible, i.e., in a test capacitor configuration.

In conclusion, this section has shown that the particular dielectric fluid chosen for a capacitor has a major effect on the total capacitor design. Consequently, and of more major importance to this study, we can further conclude that all aspects of new capacitor dielectric fluids finally need to be evaluated in the true, operational capacitor environment.

2.3.5 Test techniques and standards used by manufacturers and users to evaluate fluid-filled capacitors and cables.

The capacitor manufacturers and users have the following standards documents available for guidance in selecting and handling the insulating fluid.

1. ANSI C 59:11 (also American Society for Testing Materials (ASTM)) D2233-74 "Standard Specification for Chlorinated Aromatic Hydrocarbons (Askarels) for Capacitors."

   This document gives detailed specifications of the physical, chemical and electrical properties of four askarels which have been used as capacitor impregnants and details test methods.

2. ANSI C 59.123-1970 (also ASTM D2297) "Standard Specification for Continuity of Quality of Electrical Insulating Mineral Oil for Capacitors and Cable Accessories."

   This document provides detailed specifications of the physical, chemical and electrical properties of the oil.

MONS 047086

3. ANSI C 59.122-1970 (also ASTM D2296) "Standard Specification for Continuity of Quality of Electrical Insulating Polybutene Oil for Capacitors."

   This document provides detailed specifications of the physical, chemical and electrical properties of the oil and details test methods.

4. ANSI C 107.1-1974 "Guidelines for Handling and Disposal of Capacitor- and Transformer-Grade Askarels Containing Polychlorinated Biphenyls."

   This document gives the typical physical, chemical and electrical properties of askarels used as capacitor impregnatns, details methods of shipping and handling, spells out necessary safety precautions, recommends labeling practices and details approved disposal techniques. It also lists organizations having facilities for analysis and for disposal and details an analytical procedure for the determination of airborne PCB's.

5. IEEE Draft "Specification for New, Unused Transformer-type Askarels"

   This specification covers bulk shipment in tank cars and drums of new, synthetic, nonflammable electrical insulating liquids of the chlorinated aromatic type known as askarels which are used as insulating and cooling media in liquid-filled transformers. While this specification is intended to cover the composition and characteristics of askarels for purchase only and does not apply to liquids in apparaturs, a number of discontinued types are included for purposes of identification and historical significance.

The following standards relate to the specification and performance of the capacitor itself:

1. ANSI C 55.1-1968 (IEEE No. 18) "Shunt Power Capacitors"

   Definition of terms, ratings, tolerance, operation, production and design testing, fusing. Such characteristics as stability, corona start, radio influence voltage, overvoltage, capacitance, leakage, loss and dielectric withstand are identified, but the specific detailed test technique is not described, nor are appropriate ASTM procedures cited. This standard is for shunt power capacitors without reference to the dielectric fluid; with non-askarel fluids, certain specified values and limits might possibly have to change, and specific test procedures may not be the same as have been traditionally used for askarel capacitors.

2. ANSI C 55.2-1973 "Series Capacitors for Transmission and Distribution-line Compensation"

   This standard includes requirements for safety, rating, and gap settings; functional requirements for protective equipment, alarm devices, servicing, type, and routine tests and a guide for operation.

3. NEMA CP1-1971 "Shunt Capacitors"

   This standard is similar in coverage to ANSI C 55.1.

4. EIA RS-392 "Fixed Paper Dielectric Capacitors for Alternating Current Applications."

   This standard covers the requirements for oil-paper dielectric capacitors hermetically sealed in metal cases for general purpose application on AC voltages. It specifies (1) standard designations, (2) standard test conditions, (3) marking, (4) quality assurance test programs, (5) tests, and (6) applications suggestions. Although the term "oil" is used, this standard is meant to apply to askarel-filled capacitors.

MONS 047088

5. EIA RS-392-1 (ANSI C83.67a-1974) "Fixed Paper Dielectric Capacitors with Non-PCB Impregnant for Alternating Current Application"

   This standard applies to capacitors with paper dielectric impregnated with non-PCB fluid. Note that there is no existing EIA standard covering non-PCB capacitor fluids with plastic film dielectric.

6. EIA RS-401 "Paper, Paper/Film, Film Dielectric Capacitors for Power Semiconductor Applications."

   The coverage of this standard is similar to RS-392 above.

7. UL (Underwriters Laboratories) 10 "Power Factor Correction Capacitors" (600V).

Cables

AEIC (Association of Edison Illuminating Companies) 1-68

"Solid-Type Impregnated-Paper-Insulated Lead-Covered Cable Specifications"

This standard specifies rated voltages, preferred sizes, construction, and assembly details and tests.

AEIC 2-67 "Specifications for Impregnated-Paper-Insulated Cable, High-Pressure Pipe-Type"

The coverage of this standard is similar to 1-68 above.

IPCEA (Insulated Power Cable Engineers Association) S-67-401 (also NEMA WC2-1967) "Metallic and Associated Coverings for Impregnated-Paper-Insulated Cables"

This covers materials, constructions, and requirements for metallic and associated coverings for normal use with oil-impregnated, paper-insulated power cables.

This is the only IPCEA standard not related to solid insulation.

Note: There are also several ANSI Standards in this area.

2.3.6 References, Section 2.3

Much of the material in this section was obtained through personal conversations with the manufacturers and users cited in the introduction. In addition to these personal communications, the following publications and reports were found to be helpful:

1. R. H. Munch, "New Capacitor Impregnants," IEEE, New York, Jan. 30, 1975.

2. B. H. Goldy, W. O. Solbert, "A New Liquid Dielectric for Capacitors," Insulation/circuits, Jan., 1975.

3. John Lapp, "Concepts in Systems Testing of Dielectrics in Capacitors," IEEE PES Summer Meeting, July, 1974, T 74 450-3.

4. J. H. Wright, "Comments of Westinghouse Electric Corporation," hearings regarding "Preposed Toxic Pollutant Effluent Standards ...," Mar. 15, 1974.

5. L. L. Jackson, "Industrial Organic Chemicals as Alternative Dielectric Fluids," IEEE PES Winter Meeting, New York, Jan., 1974, C74 265-5.

MONS 047090

2.4.1 Available Fluids

In this section we shall treat a few of the major materials used at the present time in the electric power industry as transformer and capacitor fluids. The power industry in general has viewed with reluctance any change from the use of askarels in transformers and capacitors not out of prejudice or indifference to the environment or people's safety, but because the askarels possessed outstanding electrical characteristics. Furthermore, the askarels have low flammability, and, while not inexpensive, their cost has been at a level the industry could manage. It must be emphasized that there is no other fluid now available which has quite so broad a range of application and usefulness in the electric power industry. If it is decided that the askarels are not to be used in transformers and capacitors, then it will be fairly certain that two classes of compounds, one for capacitors, the other for transformers, will be required.

In addition to the high versatility of the askarels, there is the fact that the materials are cheap, although they cost more than mineral oils. The prime supplier of askarels is a major chemical company of high productive capacity which has kept the price of the material at a reasonable level. The general applicability, as well as the relatively low cost will be lost in any switch away from askarels since virtually all proposed substitutes will be more expensive. At least one of the promising substitute transformer fluids discussed below is at present being offered at a rebate, presumably in order to establish a market. It is not known whether this lower rebate price could be maintained for any great length of time.

The materials discussed briefly below constitute by no means all of the existing promising fluids proposed as substitutes for the askarels. Any such list would be immensely long and would prove to be an encumbrance to this report which is designed to provide a view of the adequacy of present test methods rather than a view of all possibilities.

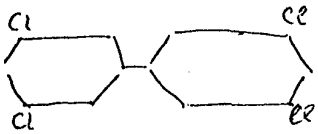
The major fluids proposed as substitutes for the askarels in power transformer and capacitor application are for transformers: (a) silicone oils, (b) mineral oils,

(c) highly saturated paraffin oils. For capacitors, the fluids are (d) long chain esters of phthalic acid and (e) diaryl sulfones of a variety of types. There are other minor fluids which will be included at the close of the discussion. However at the present time, these materials are either not so desirable electrically as the above five fluids or they are an order of magnitude (or two!) more expensive.

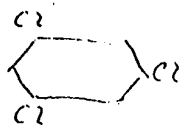
Before proceeding to the consideration of the non-askarel fluids a few remarks on the askarels themselves may not be amiss.

The Askarels (polychlorobiphenyls)

The askarels are proprietary mixtures of chlorinated biphenyls and chlorinated benzenes, the empirical formulas of which are $C_{12}H_{10-n}Cl_n$ (where n may run from 1 to 10) and $C_6H_{6-n}Cl_n$ (where n may run from 1 to 6) respectively. These compounds may be represented by the structural formulas of a single example of each.



2, 2', 4, 4' - tetrachlorobiphenyl



1, 3, 5 - trichlorobenzene

The proprietary mixtures mentioned above usually are designated as having an effective percentage of chlorine and this percentage usually appears somewhere in their trade numerical designation. The singly chlorinated biphenyls are light oils and the completely chlorinated (n = 10) biphenyls usually assume the character of a resin or wax.

Although first synthesized nearly a century ago [1], it was not until the third and fourth decades of this century that they were produced in considerable quantities [2]. It was during these decades that the superior electrical properties of these materials became apparent. Within a few years, large scale manufacture of the polychlorobiphenyls was undertaken [3]. Besides the excellent electrical properties and the low flammability of the polychlorobiphenyls it was observed that with the somewhat higher dielectric constant over, say, transformer oils, the capacitor size could be reduced [4].

The askarel fluids have been suggested as being suitable in a wide variety of applications outside the electric power industry, mostly as heat transfer fluids, additives to petroleum oils, in textile coatings and in surface coatings and paints [5]. Applications to sealing compounds, printing inks and papers, and casting waxes are all well attested [5].

The variety and successfulness of application of the askarel mixtures has led to widespread use and unfortunately to their widespread occurrence in the environment.

Most of the areas where the polychlorobiphenyls occur in the environment are, of course, associated with eminently intense industrial activity. However, the high chemical stability of the askarels insures their persistence wherever they are transported. The result is that they are found at some polluting level in a great many places around the world. The polychlorobiphenyls have been documented as existing in North and South America in both marine and freshwater environments [6-10]. A detailed discussion of these findings may be found in Kimbrough's comprehensive review paper [...].

There would seem to be little point expatiating upon the toxicity of the polychlorobiphenyls in this brief resume since this report concerns the adequacy of tests of prospective replacements for these very fluids. Suffice it to say, in summing up, that the polychlorobiphenyls accumulate, persist, and are destructive to animal tissues. Evidence for their prospective condemnation unfortunately mounts [12-16]. Kimbrough's review [11] provides details on toxic effects in animals and human beings of polychlorobiphenyls and should be consulted by the interested reader.

MONS 047094

Silicone Oils

Probably the foremost contenders among the silicone oils as a substitute for the askarels are mixtures of the dimethyl siloxane polymers. These mixtures can be made up in a variety of viscosities. One of the most important properties of the dimethylsilicone oils is their low temperature coefficient of viscosity [17]. They are also mechanically resistant to high shear rates [18, 19]. These compounds are generally inert and are resistive to oxidative and thermal degradation [20, 21].

The dimethylsilicone oils may be compounded to have viscosities running from 1 to well beyond 30,000 centistokes. The dielectric constants for all such mixtures remain in the neighborhood of 2.7 over many orders of magnitude in frequency [22] and over a broad range of voltages [25]. The flammability of the various mixtures exhibiting this viscosity range may be gauged by the range of the open cup flash point of about 37 °C for a 1-centistoke fluid to about 320 °C for a 200-centistoke fluid [22, 23

The solid-liquid transitions for the methylsiloxane oils that interest us here, occur for the most part in the neighborhood of -80 to -40 °C [22]. The dielectric strength of these fluids is in the neighborhood of 40 kV/0.1 in. [22]. The dissipation factor is about 0.0003 at 100 Hz. All in all, these fluids are nearly ideal as power transformer fluids. They do not sludge or oxidize easily and with proper design one obtains good heat transfer. They offer good resistance to acid and alkaline contaminants in a transformer. Offsetting these virtues somewhat is the fact that when these fluids are subjected to arcs their dielectric strength may be reduced by the formation of solid SiO_2 filamentary bridging. In addition there seems to be a possibility of silicon carbide, SiC, being formed at an arc in these oils. Silicon carbide is conductive, and refractory, and provides another impediment to the self healing of the dielectric liquid [24].

These drawbacks are much more detrimental to applications in capacitors than in transformers and explain why the oils are proposed mostly for transformer use.

MONS 047095

Since the breakdown products of the silicones resemble the products from which they are synthesized, a few words should be added here about the chemistry of silicone oils. What is given below is not meant to represent current proprietary methods of silicone oil production but to give elementary background material for discussions elsewhere in the report.

Early expectations that silicon would form an organic chemistry analogous to carbon organic chemistry were never fulfilled. Saturated silicon chains analogous to the paraffins can indeed be formed but the silicon-silicon bond is relatively weak. At the beginning of the century Alfred Stock prepared the first few members of the silicon hydride series by dropping [see 26] acid on magnesium silicide:

$$Mg_2SI + H\ Cl \rightarrow SiH_4 + Si_2H_6 + Si_3H_8 + \ldots + MgCl_2 .$$

He found that the hydrides were unstable and he was not able to prepare any compound in pure state higher than Si_4H_{10} [see 26]. The modern silicon compounds which are of interest here do not rely on the Si-Si bond which is subject to oxidation but upon the stable Si-O-Si bond. From this bond true polymers may be constructed as was evidenced by the thorough investigation of compounds of this class by Kipping in the first half of the century [see for instance, 27]. We might pursue one possible path to synthesis of a dimethyl silicone. If we treat sand (SiO_2) at about 1000 °C with chlorine gas and a reducing agent (carbon) an important product would be silicon tetrachloride, a corrosive liquid at room temperature ($SiCl_4$). Use of a methyl Grignard reagent (CH_3MgCl) will allow attachment of methyl groups to the silicon atom:

$$SiCl_4 + 2\ CH_3MgCl \rightarrow (CH_3)_2\ SiCl_2 + 2\ MgCl_2 .$$

The dimethyl silicon dichloride is most useful because we simply allow it to react with water:

$$\begin{array}{c} CH_3 \\ | \\ Cl - Si - Cl \\ | \\ CH_3 \end{array} + 2H_2O \rightarrow \begin{array}{c} CH_3 \\ | \\ HO - Si - OH \\ | \\ CH_3 \end{array} + 2\,HCl$$

This product is called dimethyl diallanol and will undergo a dehydrative condensation, thus:

$$\begin{array}{c} CH_3 \\ | \\ HO\,C - OH \\ | \\ CH_3 \end{array} + \begin{array}{c} CH_3 \\ | \\ HO\,Si - OH \\ | \\ CH_3 \end{array} \rightarrow \begin{array}{c} CH_3 \\ | \\ HO - Si - O \\ | \\ CH_3 \end{array} - \begin{array}{c} CH_3 \\ | \\ Si - OH \\ | \\ CH_3 \end{array} + H_2O$$

giving us a primitive dimethyl silicon. A glance at the equation will suggest to the reader that longer chains and cyclic compounds can be built up from our simple silicone, and such is the case. The last reaction may be reversed under altered circumstances, i.e., may yield silanols from silicones, a point of interest in avoidance of dumping toxic materials onto the land and into waterways of this country.

These compounds are non-flammable in the sense that they have no true combustion points. The heat supplied to the compound must be sufficient to cause depolymerization if the combustion is to be sustained; only the short chain polymers really burn [25, 28].

Mineral Oils

Most of the oils used as transformer fluids are complex mixtures of paraffinic compounds of mineral origin. Many of these paraffinic compounds are both saturated and cyclic. Such compounds are designated as "naphthenic" by the petroleum industry. The oils are nearly always the result of a process where the refining method is tailored to the final use of the product. The aromatic content of the oil must be controlled in order to prevent sludging or oxidation of the paraffin components; but some aromatics are added as oxidation inhibitors. A typical additive which is compounded with the oil as an antioxidant is ditertiary butyl paracresol (DTBP) which frequently is added at the 0.2% level [24]. Such antioxidants are largely confined to distribution transformer applications. The use of such compounds is largely avoided in power transformers where the fluid is hermetically sealed into the transformer under a blanket of nitrogen gas. The addition of aromatic compounds is also designed to inhibit gassing in an oil under the operating conditions of a transformer. However such additions may prove a two-edged sword since one and the same class of compounds can cause sludging and oxidation of the paraffin oil.

The low cost and self-healing properties of mineral oils coupled with their satisfactory electrical properties have contributed to their widespread use. These oils have a dielectric constant of about 2. The dissipation factor is about 0.001 at 60 Hz. The dielectric strength of mineral oils is generally greater than 30 kV/0.25 cm and 10^{12} Ωcm is a typical value for the resistivity of a fresh oil. The toxicity of oils composed entirely of saturated paraffins is very low. Highly saturated oils find perennial use in cosmetic products. Some of the highly refined oils are pharmacopoeal. The presence or addition of aromatic inhibitors increases the toxicity of the oils.

The degradation of a pure oil in a normal atmosphere probably follows the course of oxidation of alkanes to, ultimately, carbon dioxide and water. Such a process would require high-energy radiation (ultraviolet) for initiation of the reaction.

MONS 047098

The mechanism of this process is not yet clearly understood because of the paucity of knowledge of slow reactions [31]. All paraffins are to some slight extent soluble in water and can therefore in time react with compounds present in natural waters. Furthermore, volatile fractions of an oil may escape into the atmosphere where if they are excited by energetic radiation they may form free radicals which readily react with atmospheric components. Whatever the details of the case, it is believed that the degradation products whether produced by physical or biological means are not highly damaging to the environment.

The flammability of the mineral oils is considered high since they are hydrocarbons with no quenching atoms (such as halides). If the oil is to be suitable for transformer use it must be both insulating and non-viscous at operating temperatures since it will be used as a convective heat transfer fluid. However in a rough and ready way of speaking, the less viscous an oil, the closer it is to its flash point so that a compromise between hazard of fire and efficiency as a heat exchanger is required. These considerations have lead power companies to the use of oil in transformers and capacitors almost exclusively in exterior installations, and even there a firewall may be required (as near a wooded area, for example) or advisable.

If a transformer can be made to operate at a temperature remote from its flash point the hazard from fire would seem to be more remote than in the usual situation. There is some advocacy (see for example Duckett RTE Corp., [30]) of using high-purity high-flash-point paraffin oils in inside installations, much as askarels are used at present. The test used to suggest the suitability of such oils is discussed in the next section.

Hydrogenated Paraffin Oils

One suggested fluid for transformer use is a product which the RTE Corporation of Waukesha, Wisconsin is offering as a substitute for askarels in transformers in locations proximate to or inside buildings. The firm maintains that the high flash point and consequent low flammability of this oil so much reduces hazard from fire in proximate installations that that fluid should qualify for service in such installations.

This fluid is not produced by the RTE Corporation itself. The supplier is a large oil company [29] and the fluid was designed, or expected to be used, in high-temperature transformers. The product is marketed as RTemp. The composition does not appear to be anything unusual in the way of petroleum oils. It is a high-viscosity 800 cs (25°C), high-flash-point (296°C) oil with a dielectric strength of about 37 kV/0.25 cm, (ASTM D877), and high resistivity, 10^{13} ohm-cm. The oil is a petroleum product twice subjected to a hydrogenation process, thereby acquiring its saturated paraffinic properties. RTemp is therefore a highly stable mineral oil which is claimed to be of food grade [30]. It is presumed that the environmental characteristics of this highly saturated oil would be similar to the pharmacopoeal mineral oils [30]. That is, they form "safe" combustion and degradation products. RTemp oil is being tested by power companies in the Chicago area as noted elsewhere in this report [29]. The general physical and electrical properties of this oil resemble the ordinary transformer oils. The flammability properties of R Temp transformer oil are better than most transformer oils as would be indicated by its high flash point. The expected lower flammability is confirmed in a general way by the surge-cell tests conducted at RTE Corporation by Duckett *et al* [30]. The surge of electric energy into the oil caused

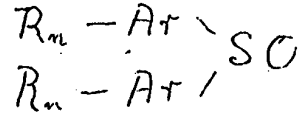
MONS 047100

vaporization of the oil and dispersal of the oil outside the test apparatus. No fire resulted, however, because the temperature of the liquid oil was well below the combustion point. This behavior was in marked contrast to an ordinary transformer oil subjected to the same test which ignited immediately and did not extinguish possibly because oil was initially closer to its flash point than the RTemp and considerable less energy was required to bring the transformer oil to combustion temperature.

Oils of the highly saturated type are used in cable and underground applications. The high viscosity of such oils makes them acceptable at the common operating temperatures of transformers in temperate or even moderately cold weather. But in the severest cold these oils require the protection of enclosure or burial to maintain their fluidity. Although the RTE surge tests show, and the combustion data predict that these highly saturated oils are probably safer than ordinary transformer oils, the National Electrical Code Committee will need independent testing before explicit acceptance of this fluid.

Mixtures Containing Diaryl Sulfone

These compounds are proposed by one of the major chemical companies of the country as substitutes for the askarels. The basic chemical structure is:



where the R is an alkyl group with probably 1 - 8 carbon atoms, n runs from 1 to 3 and Ar is a phenyl, naphthyl or indan group. All these compounds are halogen free [35]. The actual product is presumably a proprietary mixture of such compounds and other ingredients such as non-chlorinated biphenyls. Cited as example in German and U.S. Patent disclosures [35] is a mixture of tolyl xylyl sulfone, isopropylbiphenyl and minor ingredients. It is presumed that in use further ingredients will be added to these compounds as antioxidants.

The mixtures as proposed have a dielectric constant of about 6. No dielectric strength figures are available at present, but life-tests of capacitors are continually being run by the manufacturer of the fluid [36]. The fluid is tested in ballast-capacitor use at 1000 volts at 90°C working temperature. The flash point of the mixtures now advocated by the manufacturer is about 150°C, combustion is sustained at about 165°C and the fluid will auto-ignite in the region of 450°C. No pour-point figure is available but the capacitors function well at -50°C [36]. Some toxicity studies have been conducted by the manufacturer. These studies indicate that irritation can be induced by intense or prolonged contact of the mixture with eye or skin of rodents. The manufacturer recommends that normal

MONS 047102

industrial hygienic precautions be taken (attainable, in the main, with soap and water) in order to assure safe handling.

These materials when fed to rodents seem to break down into excretable metabolites according to studies conducted by, or on order of, the manufacturer. Polychlorobiphenyls fed under similar conditions persist in the animal body after the sulfone mixtures in the tissue have become undetectable.

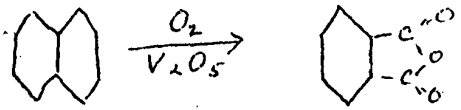
MONS 047103

The Phthalate Esters

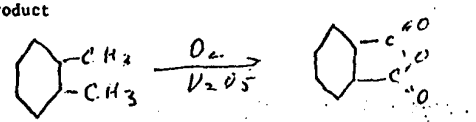
The phthalates can be offered immediately as a product for use in the high voltage capacitor industry because they are already supplied by the petroleum industry as plasticizers for polyvinyl chloride plastics in tonnage quantities. In 1972, about 1 billion pounds of some 20 different phthalate esters were manufactured [32].

The superior electrical characteristics of the esters of phthalic acid make them natural candidates as substitutes for the askarels in power-capacitor use should the substitution become necessary.

The phthalic anhydride typically is manufactured from naphthalene which is oxidized in the presence of vanadium oxide to phthalic anhydride



or alternatively from o-xylene by a similar oxidation process to the same end product



The phthalate esters supplied as high voltage insulating liquids are mostly diisononyl phthalate (DINP) and dioctyl phthalate (DOP) [33]. One major manufacturer prefers DINP over DOP because of the expected resistance to hydrolysis bestowed by steric hindrance.

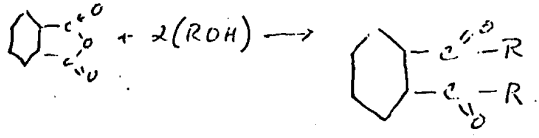
The chemical and petroleum companies use various methods for producing the alcohols from which DOP and DIOP are formed, all of which start from petroleum refinery products. They may be typified by the one reaction for

MONS 047104

2 ethyl-hexaral which begins with propylene to from a C_4 aldehade which in turn by aldol condensation yields a C_8 aldehyde. The C_8 aldehyde is hydrogenated to 2 ethyl-hexanol.

$$C_3H_6 \xrightarrow{CO_2,\ H_2} C_4 \text{ aldehyde} \xrightarrow[\text{condensation}]{\text{aldol}} C_8 \text{ aldehyde} \xrightarrow{H_2} \text{2 ethylhexanol.}$$

The 2-ethylhexanol then esterifies the phthalic acid



producing the well-know plasticizer 2 ethylhexanol. The octanols and isononanols used in the manufacture of insulating fluids will use the same or similar reactions in their preparation.

The aromatic dibasic phthalate esters typified by diisononyl and dioctyl phthalate have specific resistances in the neighborhood of 10^{12} ohm-cm. In applications as capacitor fluids they offer a dielectric constant of about 5 which is considerably higher than that offered by the askarels, and should therefore allow for more compact design of capacitors than the askarels. The voltage breakdown point occurs at around 30 kv/.25 cm. The boiling point at reduced pressure (5 mm Hg) is about 250°C, and yet the pour point is in the neighborhood of -50°C. The flash point as determined by the Cleveland Open Cup Method for these fluids is in the neighborhood of 220°C and the same determinations show that combustion is sustained at 250°C or thereabout [34].

MONS 047105

The dibasic phthalate esters are available on the market, apparently in any quantity desired and are marketed by at least two major chemical companies. At least one high voltage equipment manufacturer has modified the design of his power capacitors to accomodate the phthalates as capacitor fluids [33].

Alkyalated Chlorodiphenyl Oxides

(This section is still in preparation - - will be forwarded to reviewers at a later date.)

MONS 047106

2.4.2 Test techniques and standards by which fluid material properties are evaluated

Insulating fluids for transformers and capacitors are commonly tested and evaluated in accord with one of the following:

1. ANSI C'59.2 (also ASTM D117) "Standard Methods of Testing Electrical Insulating Oils"

2. ANSI C 59.62 (also ASTM D901) "Standard Methods of Testing Askarels"

3. ANSI C 59.118 (also ASTM D2225) "Standard Methods of Testing Silicone Fluids for Electrical Insulation"

The test procedures called out in these documents are tabulated below.

	ASKARELS (D901)	ELECT. INS. OILS (D117)	SILICONE FLUIDS (D2225)
Acidity, Approximate	D974	D1534	
Acidity, Approximate, and Polar Contamination		D1902	
Coefficient of Thermal Expansion	D1903	D1903	
Color	D2129	D1500	D2129
Chlorides, Inorganic	D1821	D878	
Chlorine Compounds, Hydrolyzable	D1820, D2441		
Dielectric Constant	D924		D924
Dielectric Strength Using Metal Disk Electrodes	D877	D877	
Dielectric Strength Using VDE Electrodes		D1816	
2,6 Ditertiary-Butyl Para-Cresol Content		D1473	
Examination, Visual		D1524	
Flash Point		D92	D92
Fire Point	D92		
Gas Content		D831	
Gas Content (Nonacidic)		D1827	
Inorganic Chlorides and Sulfates		D878	
Interfacial Tension		D971	
Neutralization Value (Neutralization Number)	D974, D664	D664, D974	D974
Oxidation Stability		D2440*	
Peroxide Number		D1563	
Pour Point	D97	D97	D97

MONS 047107

	ASKAREL®	ELECT. INS. OILS	SILICONE FLUIDS
Power Factor	D924	D924	D924
Refractive Index (and Specific Optical Dispersion)	D1807	D1807	D1807
Resistivity	D1169	D1169	
Sampling	D923	D923	
Saponification Number		D94	
Scavenger Content	D1701		
Sediment and Soluble Sludge		D1698	
Sludge		D1313, D1314	
Specific Gravity	D1810	D1298	D1298
Specific Resistance			D1169
Sulfur, Corrosive		D1275	
Thermal Stability	D1936		
Viscosity	D88, D445	D88, D445, D2161	D445, D2161
Visual Examination	D1702		
Volume of Oil	D1808		
Water Content	D1533	D1315, D1533	

*D2112 also deals with oxidation stability and is called out in D3146, "Standard Specification for Oxidation-inhibited Mineral Oil for Use in Transformers and Circuit Breakers"

The following ASTM Standards have recently appeared:

D3300 "Standard Method of Test for Dielectric Breakdown Voltage of Insulating Oils of Petrolium Origin Under Impulse Conditions"

D3303 "Standard Method for Rapid Gas Chromatographic Estimation of Higher Boiling Homologues of Chlorinated Biphenyls for Capacitor Askarels"

D3304 "Standard Method for Analysis of Environmental Materials for Polychlorinated Biphenyls" (This document is a modified version of Appendix B of ANSI C107.1-1974).

2.4.3 Test techniques by which fluid flammability is evaluated.

Most would agree that the concepts of combustion and flammability of a material are qualitatively clear and easily understood. The quantitative definitions of flammability of the material, that is, whether it will ignite and then continue to burn under specified temperature, pressure and ambient atmosphere conditions is not, however, as easily achieved. What is required is a flammability test in which all relevant parameters are rigorously controlled and in which the results are unequivocally interpretable, and this has been difficult to develop to everyone's satisfaction. The various tests which are recognized and in common use are described below, along with comments on their applicability and shortcomings:

a. Flash and fire points

The only test specified by the standard-setting agencies (ASTM, ANSI, NFPA, IEEE) for insulating fluids, mineral oils and askarels, is the Cleveland Open Cup test for flash and fire points (ASTM D-92). The specifications are:

Mineral oil: flash point of 146°C (in some areas 130°C);

Askarel: no fire point up to boiling point.

Beside the D-92 test, ASTM recognizes several other variants for determining the flash point, which, however, are not prescribed for insulating fluids: the Tag Open Cup tester (D-1310), the Tag Closed Tester (D-56), and the Pensky-Martens Closed Tester (D-93). In all experimental arrangements the flash point is determined by slowly increasing the temperature of the cup containing the liquid sample. An ignition source, placed above the surface of the liquid, is actuated at specified intervals. The flash point, by definition, is the lowest temperature of the cup at which the vapors above the liquid surface flash. The flashes are transient, because only the vapor phase burns, not the liquid. In

MONS 047109

addition to the determination of the flash point, the D-92 test specifies the procedure of increasing the temperature beyond the flash point up to the temperature at which transient application of the ignition source causes continued burning of the liquid. The lowest temperature at which this happens is the fire point. Determinations of flash and fire points give valuable indications of flammability hazards, and should continue to be used. However, it must be recognized that developments in recent years have progressed significantly beyond the stage at which the standards for insulating fluids were set, and also beyond the state-of-the-art prescribed by officially adopted ASTM standards. The following items should be considered before flash and fire point standards are recommended for replacement fluids:

(1) There has been a general trend toward closed-cup methods (e.g., D-93). In particular, Underwriters' Laboratories have favored closed-cup tests for some time now. These generally give lower flash points than the open-cup variants. For example, the flash points of the Dow Corning 50CS (silicone) fluid are 304°C and 277°C as determined by D-92 and D-93 tests respectively.

(2) The ASTM Flash Point Committee is moving toward recommending international adoption of an "equilibrium" method. Equilibrium methods specify Flash-No Flash determination at a series of constant (rather than continually increasing) temperatures. Since in equilibrium methods the entire system, sample and container, is at the same temperature, complications associated with heat transfer between the sample and the container are eliminated. Therefore sample size is arbitrary and much

MONS 047110

smaller samples can be used. In addition, these methods do not depend on viscosity because convective currents within the sample are also eliminated.

(3) Scientific analyses of fire-point determination are poorly developed. Therefore, the significance of the test is not clearly understood. This point will be further discussed in connection with the Oxygen Index test.

b. The Oxygen Index Test

In the Oxygen Index (OI) test the test sample is placed inside a tube containing a mixture of oxygen and nitrogen gases. The gas mixture, normally at room temperature, flows gently upward. The sample is ignited and the percentage of oxygen in the gas mixture is decreased. OI, by definition, is the percentage of oxygen in the oxygen/nitrogen mixture at which extinction occurs.

The specified ASTM OI technique applies to solid samples only (D-2863). Various laboratories have made their own modifications of the test to apply it also to liquids, and have reported the resulting data, but there is no uniformity of procedure.

Sharply divided opinions exist as to the value of the OI test toward a definition of flammability. For example, a limited polling of the industrial opinions in this survey shows that some manufacturers use the test for practical purposes, while others consider it "worthless." The reasons for this division are not difficult to see. On one hand, it is recognized that the burning of a small laboratory sample (grams) in room-temperature environments in no way simulates the behavior of large amounts of combustible materials in a well-developed fire. On the

other hand, there are reasons why the OI test should not be discounted in the context of this survey. Fundamentally, the test is the prototype of extinction of a diffusion flame, and it bears roughly the same relationship to practical fire-point determinations that the fundamental flammability-limit data do to practical flash-point determinations. As was discussed earlier, both flash and fire points are specified standards for definition of flammability of insulating fluids. The problem is, however, that fundamentally meaningful fire-point, or OI, tests are more difficult to design than the meaningful flash-point tests.

To obtain consistent extinction data one would have to develop an OI test for liquids and a fire-point tester in such a way that an OI value of 21 (i.e., air) is obtained at the experimental fire point. Recent work at the NBS Center for Fire Research shows that such development would require very careful design of the test geometry. Therefore, an OI test for insulating fluids should be recommended only after some additional study, allowing specifications of the testing arrangement.

c. Spray Flammability Tests

The ASTM Mist Spray Flammability of Hydraulic Fluids test (D-3119-72T) could be applied also to electric insulating fluids, but we have no evidence that anyone has done that. The test is a very severe one, entailing the spraying of a preheated atomized mist into an open flame. Underwriters' Laboratories consider it too severe and use one of their own variants in its stead (UL File MH 01466, p. T1-6). The UL test consists of applying drops of the liquid to the surface of a heated steel plate, and observing the "behavior."

MONS 047112

Factory Mutual Research Corporation has its own spray flammability test, akin to D-3119. It is also a very severe one. Most hydraulic fluids do not pass it.

Inasmuch as our survey of actual or potential accidents (admittedly a very limited one so far) has revealed no practical circumstances which would be simulated by any of these droplet-combustion tests, there is no reason why they should be recommended for replacement fluids. Further survey of accidents may give ground for a firmer recommendation.

d. Autoignition Temperature (AIT)

Several techniques exist for the heating of liquids in air until they ignite. ASTM D-2155 is a specified procedure for liquid petroleum products. Underwriters' Laboratories use a similar test of their own.

As one should expect, autoignition temperatures of electric insulating fluids are quite high. Some reported values are: 332°C for a mineral oil and 393°C for Dow Corning 5OCS fluid, both by the D-2155 test; 662-670°C for askarels by the UL test.

As in the case of the spray flammability tests, operational conditions, normal or abnormal, are unlikely to give rise to these temperatures in the case of insulating fluids. The AIT test, therefore, does not appear particularly pertinent. (At this point, it should be mentioned that Underwriters' Laboratories do not evaluate liquids only on the basis of tests which simulate some aspects of actual operations, but also on the basis of the total information about stability and flammability of the liquid. If this philosophy is adopted, then of course the AIT test and any other reproducible test which can be tied to some property of the liquid, becomes pertinent. In fact, UL did use the AIT test among others, to arrive at a numerical flammability rating of askarels).

e. Energy-Release Tests

Hazards tests designed to evaluate the amount of explosive energy released in an accident apparently have not been used in connection with insulating fluids, but there are good reasons why they should be. Such tests almost invariably give a measure of energy release by the effect on the surroundings: damage to a target, displacement of a target, or generation of a blast wave in air. Since the hazard of an arc-initiated fire in a transformer or capacitor tank may be due to the blastwave damage as well as the subsequent fire, a measure of the explosive energy release capability of an insulating fluid would appear to be useful. Such a test would be particularly important if it could be shown to be a useful screening mechanism before going to the more expensive, full-unit tests suggested in Sections 2.2.3 and 2.3.3. Direct measurement of the blastwave intensity may be the most valid energy release test, as described more fully in Section 3.

The accompanying Table summarizes presently accepted flammability data on several insulating fluids.

MONS 047114

FLAMMABILITY DATA (1)

Info. Source	Liquid Description	Flash (°C)	Fire (°C)	AIT	OI
ASTM Stand.	Mineral Oil	146 (130)	--		
Bu Mine	Min. Oil, paraffinic (deep waxed)	196	221	371	
Dow Corning 1974 IEEE	Transformer Oil (ASTM D92)	150	165		--
	" D2155			332	
	" D2863 (Mod)				15.1
ASTM Stand.	Askarel	No fire pt. up to b.p.			
UL (closed cup)	Aroclor 1016	174	--	670	
Bu Mine	Aroclor 1242 (Trichlorodiphenyl)	177	334		
	Aroclor 1254 (Tetra-)	193	None		
Dow Corning 1973 Doble	Askarels "have no true flash point."				
	Silicones				
Dow Corning 1974 IEEE	50 CS (Polydimethyl)	304	360	393	
UL	Dow C 50CS closed cup XF-1-4701	277	445		
Dow Corning 1973 Doble	Phenylmethyl (Si)	304			
	Dimethyl (hi visc.)	319			
	" (low visc.)	138			
Bu Mine	Methyl phenyl	271			
	Polymethyl (low visc.)	124	138		

MONS 047115

FLAMMABILITY DATA (II)

1. UL Classified Prod. Index also gives info. on combustibility in air.

   Dow Corning 50CS: Moderate in air 257°C
   XF-1-4701: " " " 256°C
   Compare flash-open: 304°C, closed: 277°C

   Aroclor 1016: Moderate in air 144°C

2. Dow Corning, 1974 IEEE Paper

	Transf. Oil	50CS
Burning rate (gm/sec)	0.0267	0.0060
Mist Spray (D3119)	Violent	Spasmodic

MONS 047116

Fluid flammability measurement, by whatever test procedure is adopted, should be carried out under conditions as closely approaching operation as reasonably possible. In particular, pressure and temperature conditons are known and should be duplicated. Thus, power transformers of the "askarel class" have a temperature increase of about 65°C under full load, so that bulk fluid temperatures will probably not exceed 100°C even on hot days. Local temperatures near the transformer winding may be ten to twenty degrees higher. Most utilities operate their transformers with a pressure relief valve as prescribed by the National Electrical Code (Section 450-23); the relief pressure is usually only a few psi.*

Power capacitor tanks rupture at low (a few psi) pressures but small industrial type capacitors generally are sealed to 40-50 psi. The fluid temperatures within capacitors would not be much above the ambient, which itself might vary widely depending on location.

For a new fluid, with different loss and heat transfer characteristics, these typical values may have to be revised.

MONS 047117

2.4.4 Test techniques by which toxicity is evaluated

(This section is still in preparation--will be forwarded to reviewers at a later date).

2.4.5 Test techniques by which degradability is evaluated

(This section is still in preparation--will be forwarded to reviewers at a later date).

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MONS 047119

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2.4.26 Stock, A., and Somieski, C., Ber. 1916, 49, 111.

2.4.27 Kipping, F. S., Proc. Roy. Soc. 1937, 159A, 131.

2.4.28 McGregor, R. R., Silicones and Their Uses, McGraw-Hill Book Co., New York, 1954.

2.4.29 Link, E., RTE Corporation -- personal communication.

2.4.30 Duckett, D. A., Paper before the General Meeting of the Edison Electric Institute, Transmission and Distribution Committee, Minneapolis, Minnesota, May 8, 1975.

2.4.31 Morrison, R. T., and Boyd, R. N., Organic Chemistry, Allyn & Bacon, New York, 1966.

MONS 047120

2.4.32 Graham, P.E., Environ. Health Perspect., 1973, 3, 3.

2.4.33 Forster, E. O., personal communication.

2.4.34 Rutkowski, A. J., and Forster, E. O., presented at American Power Society (IEEE) Winter Power Meeting, New York, 1975, also Proc. VII Int. Conf. on Electrical Insulating Materials, Inst. Elec. Eng. Tokyo, Japan, 1974.

2.5 The Scope and Influence of Government Regulations

The purpose of this section is to identify the several government agencies which have potential regulatory power over new insulating fluids, to describe the particular area of concern over which each exercises regulatory power, and to define what criteria and procedures are used to determine whether a new fluid falls within the purview of each particular agency or regulation. The emphasis will, therefore, be on the regulations themselves; criteria and testing procedures which support or are cited in these regulations will be briefly identified, in Section 2.4.2, these test techniques are more thoroughly explored.

2.5.1 Environmental Regulations

Environmental protection regulations are developed and enforced by the Environmental Protection Agency (EPA) and by the various state departments of natural resources. The state agencies generally follow the Federal regulations, and they may in fact have operational responsibility for enforcing the Federal environmental regulations. Being more closely in touch with the local issues and being under less complex operating constraints, the states can often act more rapidly than the Federal enforcement agencies. It is important, therefore, that the state and Federal environment regulatory bodies act under rigorous, quantitatively definable criteria in establishing and enforcing their regulations. We will review the existing and pending Federal regulations, recognizing that these will also probably be reflected in any state acts.

Insulating and dielectric fluids are typically very stable compounds which have low vapor pressures and which, therefore, do not represent a

significant air pollution problem.* The primary environmental effect is in water, and so the primary source of environmental regulation of such fluids is:

Public Law 92-500 (86 Stat. 816)
"Federal Water Pollution Control Act Amendments of 1972"

Three sections in this act are of particular importance for evaluating the impact of regulations:

1. Sec. 307a "Toxic effluents" A proposed list and a final list of toxic substances were published by EPA in the Federal Register on 7/6/73 (38FR18044)** and on 9/7/73 (38FR24342), respectively. Criteria for selecting these substances were included, thereby indicating the standards by which new substances can be evaluated. The toxic substance list is not enforceable, however, until standards for allowable levels of these toxic substances are finally promulgated. Although standards were proposed on 9/7/73, these have not yet reached final legal status.

2. Sec. 311 "Oil and Hazardous Substance Liability" (Spills, leakage, pouring hazardous substances into navigable waters of the U.S.) On 9/22/74, proposed rules were issued: "Designation and determination of removability of hazardous substances from water" (39FR30466). A list of hazardous substances and selection criteria were included. This never reached the final promulgation stage and is in fact now being rewritten. The existing oil spills regulation (38FR34164) may serve as a guide for the new proposal.

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*See Section 2.5.3, "Occupational health," for air quality criteria in the working place.

**Federal Register (FR), vol. 38, page 818044, July 6, 1973.

3. Sec. 402 "Pollution discharge permits" This section empowers the regional offices of EPA to issue permits limiting the allowable levels of pollutants in effluent discharges. Limitations on polychlormated biphenyls have already been included in several permits. "Pollutant" is defined (in Sec. 302) as effluents which "would interfere with the attainment or maintenance of that water quality in a specific portion of the navigable waters which shall assure protection of public water supplies, agricultural and industrial uses, and the protection and propagations of a balanced population of shellfish, fish and wildlife, and allow recreational activities in and on the water,..."

In addition to the existing legislation cited above, Congress is in the process of working on a Toxic Substances Control Act, which would give EPA more direct control on production and use of identified toxic substances.

2.5.2 Poisonous Ingredients in Foods

The Food and Drug Administration (FDA), an agency of the Federal Department of Health, Education and Welfare, has the responsibility for administering the consumer protection standards established by the Federal Food, Drug, and Cosmetics Act of 1938 with amendments (FFDCA) (U.S. Code, Title 21). The various state departments of public health cooperate in maintaining proper food standards, under authority of state public health legislation. Whereas FDA enforcement authority concerns only foods involved in interstate commerce (Sec. 703 and 704 of FFDCA), the state may, of course, take local action.

MONS 047124

"Poisonous substances" include all substances documented to be harmful to human health. Thus, they may be specifically identified in FDA regulations (as in the case of PCB's; see 38FR18096, July 6, 1973) or known to be poisonous from other reliable sources such as "The Toxic Substances List" published by the National Institute for Occupational Safety and Health (see Sections 2.5.3 below). Likewise, tolerance levels are not specifically identified by FDA for each known poison, but rather this is judged on a case-by-case basis, as specified in Sec. 406 of FFDCA.

Any new insulating or dielectric fluid which is identified by any Federal agency to be poisonous would thus come within FDA jurisdiction. In relation to this, it should be noted that the FDA regulations on PCB's (38FR18096) specifically exempts PCB transformers and capacitors; being in sealed containers was an influential factor in this decision.

In enforcing its regulations, FDA can request a manufacturer to recall an adulterated product, under threat of prosecution. It can, under court authority, seize a shipment of adulterated food. And it can legally prosecute manufacturers of illegally adulterated foods. Actions are reported in:

"FDA Weekly report of seizures, prosecutions, injunctions, field corrections and recalls," published weekly by the FDA Press Office, Rockville, MD 20852.

2.5.3 Occupational Health

The Occupational Safety and Health Administration (OSHA), a part of the Department of Labor, has the responsibility "to assure so far as possible every working man and woman in the Nation safe and healthful working conditions..." as stipulated in:

MONS 047125

Dielectric and insulating fluids could come within the scope of OSHA regulations in two ways:

1. During processing of the material by the capacitor and transformer manufacturers
2. By use of the capacitors and transformers in or closely adjacent to work areas.

In the Act cited above, the following responsibilities are defined:

1. The Secretary of Labor (i.e., OSHA) is to promulgate standards for toxic substances (Sec. 6).
2. The Secretary of Labor (OSHA) also is empowered to inspect working places (Sec. 8) and to enforce the standards (Sec. 10, 17).
3. The Secretary of Health, Education and Welfare, through its agency, The National Institute of Occupational Safety and Health (NIOSH) is to carry out research, develop criteria, and carry on training concerning health and safety in the working place (Sec. 20, 21, 22).

Thus, NIOSH has the job of establishing standards, while OSHA promulgates and enforces these standards. The following publications and standards have resulted regarding toxic substances:

"The Toxic Substance List--1974 Edition" NIOSH, Rockville, MD 20852 June 1974.

In this publication, a large number of toxic substances are listed, along with toxic dose levels, and the reference sources for these toxic doses. Four PCB's are included. A new issue of this is now in preparation.

"Occupational Safety and Health Standards," 39FR23502, June 27, 1974. Sec. 1916.93 (CFR Title 29 - Labor)

Table G1 lists contaminants, including chlorodiphenyl (42% Cl); skin 8-hour time weighted average exposure not to exceed 1.0 mg/m^3, and chlordiphenyl (54%), 8-hour time weighted average skin exposure not to exceed 0.5 mg/m^3.

The source of these standards is 41 CFR 50-204.50 which cites: "Threshold Limit Values of Airborne Contaminants for 1968," Amer. Conf. of Govn. Industr. Hygienists.

The National Electrical Code (NEC) - 1971 (ANSI C1-1971) has been incorporated within OSHA regulations (29CFR 1910.308; see 39FR23502, June 27, 1974). Dielectric fluids for transformers and capacitors therefore fall within OSHA regulations insofar as these fluids are affected by the NEC. (See Section 2.6 of this report for further discussion of the NEC.)

MONS 047127

2.5.4 Transportation

The Department of Transportation (DOT) is involved in both the use and the control of insulating fluids in these two ways:

1. Use. High speed mass transit systems employ electric traction. The electric transformer is, therefore, a rather key item. It must be small because of the size limitations on the transit cars and fireproof in the event of an accident. Askarel transformers are, therefore, universally used in present ground electric transit systems.* DOT may, therefore, be a significant participant in the move toward both safe and reliable techniques for continued use of PCB's and for substitutional use of new insulating fluids.

   There is little documentation which has yet come to our attention on work by DOT on improved transformers.

2. Control. The transportation of hazardous materials falls within DOT's regulatory power, as identified in:

   49CFR Parts 100-199 Transportation; revised as of October 1, 1975.

   The following sections are particularly pertinent to the insulating fluids question:

   1. List of Hazardous Materials; sec. 172.5
      a. None of the PCB's, by any of their chemical or trades names, is on the list.
      b. Any substance which qualifies for the list under definitions given in other sections must be treated as if on the list.

*The Japanese retained askarel in their electric rail cars even after their otherwise complete ban on PCB's; they apparently are now experimenting with a silicone substitute.

2. Dielectric and Insulating fluids would be identified as Class B poisons if they were found to be toxic. (See Sec. 173.343)

3. Class B poison ("less dangerous") sec. 173.343 liquid or solid substance "known to be so toxic to man as to afford a hazard to health during transport, or which, in the absence of data on human toxicity...fall within any one of the following categories:

   1) Oral Toxicity: produce death within 48 hours in half or more of a group of 10 or more white laboratory rats weighing 200 to 300 grams at a single dose of 50 milligrams or less per kilogram of body weight when administered orally.

   2) Toxicity on inhalation: those which produce death within 48 hours in half or more than half of a group of 10 or more white laboratory rats weighing 200 to 300 grams, when inhaled continuously for a period of one hour or less at a concentration of 2 milligrams or less per liter of vapor, mist, or dust, provided such concentration is likely to be encountered by man when the chemical product is used in any reasonable foreseeable manner.

   3) Toxicity by skin absorption: those which produce death within 48 hours in half or more than half of a group of 10 or more rabbits tested at a dosage of 200 milligrams or less per kilogram body weight, when administered by continuous contact with the bare skin for 24 hours or less.

   The foregoing categories shall not apply if the physical characteristics of the probable hazards to humans as shown by experience indicate that the substances will not cause serious sickness or death. Neither the display of danger or warning labels pertaining to use nor the toxicity tests set forth above shall prejudice or prohibit the exemption of any substances from the provisions of Parts 170-189 of this chapter. (29 FR 18753, Dec. 29, 1968, as amended by Amdt. 173-3, 33 FR 14922, Oct. 4, 1968; 33 FR 19823, Dec. 27, 1968.)

MONS 047129

4. Effect of list Proper procedures for the transport of hazardous materials are stated in the following sections:

Pt. 173 Shippers
173.344 Packing for class B poisons, liquid

a) Closing and cushioning. All containers must be tightly and securely closed. Inside containers must be cushioned as prescribed, or in any case when necessary to prevent breakage or leakage.

b) Outage. Outage for containers of liquid poison for transportation by carriers by rail freight, rail express, highway, or water must be as follows:

1) Containers must not be entirely filled. Sufficient interior space must be left vacant to prevent leakage or distortion of containers due to the expansion of the contents from increase of temperature during transit.

2) The proper vacant space (outage) in a tank car or other shipping container depends on the coefficient of expansion of the liquid and the maximum increase of temperature to which it will be subjected in transit. Outage must be calculated to the total capacity of the container.

3) Liquid poison must not be loaded into domes of tank cars.

4) In tank cars, outage must be calculated to percentage of the total capacity of the tank, i.e., shell and dome capacity combined. If the dome of the tank car does not provide sufficient outage, then vacant space must be left for the shell to make up the required outage.

5) The outage for tank cars must not be less than 1 percent.

6) No cargo tank or compartment thereof used for the transportation of any liquid poison shall be completely filled; sufficient space shall be left vacant in every case to prevent leakage from or distortion of any such cargo tank by expansion of the contents due to rise in temperature in transit, and such free space (outage) shall be sufficient in every case so that such cargo tank shall not become entirely filled with the liquid at 130°F.

MONS 047130

173.345 Exemptions for poisonous liquids, Class B.

a) Poisonous liquids, class B, as defined in 173.343, except those for which no exemptions are provided as indicated by the "No exemption" statement in 172.5 of this chapter, or as provided for in 173.359(c), in tightly closed inside containers, securely cushioned when necessary to prevent breakage and packed as follows, are exempt from specification packaging, marking, and labeling requirements, except that marking name of contents on outside container is required for shipments via carrier by water. Shipments for transportation by highway carriers are exempt also from Part 177 of this chapter, except 177.817, and Part 397 of this title.

1) In glass or earthenware containers not over 1 quart capacity each, or in metal containers or polyethylene bottles not over 1 gallon capacity each, packed in strong outside wooden boxes or barrels.

2) In glass or earthenware containers not over 1 pint capacity each, or in metal or polyethylene containers not over 1 quart capacity each, packed in strong outside fiberboard boxes.

173.414 Poisons material labels

Pt. 174 Rail Freight
174.532 Loading other hazardous materials
174.538 Rail freight; loading and storage chart of hazardous material
174.586 Handling hazardous materials, by carriers by rail freight.

Pt. 175 Carriers by Rail Express

Pt. 176 Rail Carriers in Baggage Service
176.702 Hazardous materials

Pt. 177 Public highway carriers
177.821 Hazardous materials forbidden or limited for transportation
177.841 Loading; poisons
177.848 Loading and storage chart of hazardous materials
177.860 Accidents or leakage; poisons

Pt. 178 Shipping container specifications

Pt. 179 Specifications for Tank Cars

2.6 The scope and influence of insurance and fire code requirements.

In addition to the various federal and state governmental regulations which might restrict the use of fluids in electrical equipment, one must also make sure that such equipment does not conflict with insurance and fire code regulations. The two are closely related and therefore can be most easily discussed together.

The National Electrical Code (NEC) is one part (volume 6, 1975) of the National Fire Codes, issued by the National Fire Protection Association (NFPA). This code is developed and continually updated by a set of committees which is sponsored by NFPA and is composed of representatives from manufacturers, users, fire insurance companies, independent testing laboratories, and municipal and state fire safety and regulatory agencies. As such, it is an authoritative work universally recognized as a standard statement of safe electrical fire practice.

Although the NEC is not in itself law, it is usually adopted with various levels of modification as the legal electrical building code. Equipment to be legally installed within the jurisdiction of such a code must therefore conform to NEC.

As presently written, the NEC specifically recognizes mineral oil and askarel as insulating fluids. Since no more general descriptions or definitions are given, one is led to infer that other fluids are excluded unless specifically identified in future editions. To get a new material listed in the NEC, the manufacturer must propose the desired inclusion to the Electrical Coordinating Committee of NEC, along with evidence substantiating the fire safety of the material. Before approval, however, the committee would probably require testing and safety verification by an independent laboratory such as Underwriters Laboratory (UL) or Factory Mutual Engineering and Research (FMER).

UL is an independent not-for-profit testing laboratory which carries out tests on products for manufacturers and makes "listing" or "classification" judgement based on these tests:

"listing" The product is deemed to meet the requirements of the NEC.

"classification" A material will be given a flammability classification, based on a scale between 0 (water) and 100 (diethyl ether); the procedure is outlined in: "Tests for comparative flammability of liquids," UL Standard No. 340.

Whereas NEC is an installation guide, local ordinances will often look to the UL listing to verify that the product meets NEC standards and therefore can be installed as directed by the code.

FMER is a service arm of the Factory Mutual System of insurance companies. It carries out testing of equipment and issues "approvals" or "acceptances" based on these tests:

"approval" The product is deemed to be safe and suitable for general applications.

"acceptance" A particular installation of equipment and materials meets fire safety standards.

Such a safety test could be initiated upon request by a manufacturer or by one of the FM insurance companies.

An installation of electrical equipment must not only meet fire ordinances but also must be covered by fire insurance. The insurance rates are generally set by the State Insurance Commission, but an insurance company must have verification of the safety of the installation before agreeing to write insurance coverage. The insurance inspector will therefore generally look to UL or FM

acceptance, or to some other indication that the installation meets NEC requirements. The inspector might also base his decisions on his company's rating of the requesting company and possibly on the users or manufacturer's own tests.

An experimental unit with a new insulating fluid might for instance be accepted for further field testing under this latter situation. If one unit within a larger installation does not meet standards, temporary approval may be granted with the understanding that the substandard unit be upgraded to an acceptable level within a specified period.'

It should be noted that utilities are often self insured and are granted exclusion from the local codes based on NEC. It is the general practice of utilities to comply with NEC, however, and they often work closely with local fire protection people to make electrical installations safe. When utility owned equipment is installed in users buildings, often the local code or insurance requirements would necessitate that NEC practice be followed.

A further note on the NEC is that it has been adopted in toto by OSHA ("Occupational Safety and Health Standards," 29CFR 1910.308 - See 39FR23502, June 27, 1974) and it therefore has a very broad legal importance in industrial facilities. OSHA regulations are discussed more extensively in Section 2.5.3.