EPA 560/6-77-008

ASSESSMENT OF THE USE OF SELECTED REPLACEMENT FLUIDS FOR PCBS IN ELECTRICAL EQUIPMENT

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

March 1979

U. S. Environmental Protection Agency
Office of Toxic Substances
Washington, D. C. 20460

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FINAL TASK REPORT

Submitted to:

U. S. Environmental Protection Agency
Office of Toxic Substances
Washington, D. C. 20460

Attention: Mr. Thomas Kopp
Project Officer

Contract No. 68-01-3259, Task VII

Submitted by:

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March 1, 1979

PREFACE

This report on the substitutes for PCBs in electrical equipment is one of a series of reports that have been prepared by Versar for the Environmental Protection Agency under contract 68-01-3259. All of this work has been in support of regulatory activities involving PCBs. Mr. Thomas E. Kopp of the Office of Toxic Substances, has been the EPA Program Manager throughout the performance of this contract.

The electrical equipment manufacturing industry was faced with a serious problem when the use of PCBs was banned by the Toxic Substances Control Act. PCBs had unique properties when used as fire resistant dielectric liquids in transformers and capacitors, and had been almost the only liquid used in these electric applications over the past 45 years. The equipment manufacturers were faced with the challenge of redesigning their products to achieve adequate performance and fire safety from substitute liquids which did not equal PCBs in either property.

This report has been under preparation for over two years, and has been constantly updated as the technology of replacement liquids has evolved. Portions of the material that was prepared for this report were used by Versar in support of the PCB Work Group that prepared the regulations, and Versar's analyses of the economic impacts of the regulations also relied heavily on the material in this report. The report is being published now as a summary of the developments in the electrical equipment industry at the time that the EPA is promulgating the final PCB Ban Regulations.

Special thanks are due to Mr. Kopp for his patient support during the performance of this contract over the past three years. Thanks are also due the many technical experts in the electrical equipment industry who discussed their problems and developing solutions with Versar and so made this report possible.

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1.0 INTRODUCTION

Polychlorinated biphenyls (PCBs) are a family of chlorinated organic chemicals that have been used in various industrial applications in the United States since 1929. PCBs have been used in numerous applications because of their chemical stability, low vapor pressure, low water solubility, and moderate price. These characteristics, combined with special electrical properties, led to the nearly universal use of PCBs as dielectric liquids in A.C. lighting, ballast capacitors, industrial capacitors, and power factor capacitors. PCBs have also been widely used as fire-resistant, heat transfer electrical insulating liquids in those liquid-cooled transformers, electromagnets, and electric motors that were installed in hazardous locations. PCBs were widely used in non-electrical applications such as heat transfer and hydraulic fluids, dye carriers in carbonless copy paper, and as plasticizers. It has been estimated that about 75 percent of the 1,250 million pounds of PCBs used in the United States was used in electrical equipment.[(1)]

The major manufacturer of PCBs in the United States was Monsanto Chemical Company, which marketed various mixtures of PCBs under the trade name "Aroclor" - 1200 series. The PCBs were made by reacting biphenyl with chlorine in the presence of ferric chloride, resulting in the substitution of chlorine for hydrogen on the biphenyl molecule. The average degree of chlorination depended on the time that the reaction was allowed to continue. After further processing to remove residual HCl and byproducts, the mixture of various chlorinated species was described by the average weight percent of chlorine in the mixture, i.e., Aroclor 1242 contained 42 percent chlorine by weight. The reaction can be described by the following equation:

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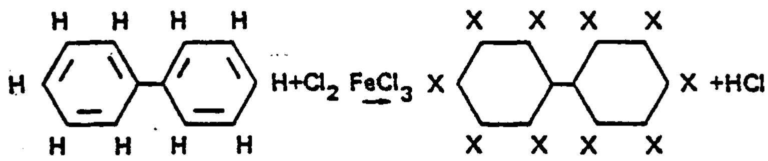
(1) Versar, Inc., PCBs in the United States: Industrial Use and Environmental Distribution. Springfield, Va.: National Technical Information Service (NTIS PB 252-012/3WP), February, 1976.



BIPHENYL ($C_{12}H_{10}$)   X = Cl or H

This reaction can theoretically result in any of 209 different chlorinated biphenyls, depending on which hydrogen atoms are replaced by chlorine and the number of hydrogen atoms replaced. Most commercial Aroclors contained only 30 to 40 different species of PCB in significant amounts. Monsanto marketed mixtures containing from 21 percent chlorine to 68 percent chlorine for various electrical and non-electrical uses.

Prior to 1968, PCBs were recommended for a great number of uses because of their chemical stability and the wide range of viscosities that could be obtained as a function of average chlorine content. Little thought was given to the eventual fate of the PCBs, and the only health effects publicized were related to chloracne caused by skin contact. In 1969 and 1970, a number of events occurred that demonstrated the chronic toxicity of PCBs and their presence in the environment at significant levels. In 1968, an industrial accident in Japan caused the contamination of cooking oil with PCBs. Distribution and use of this oil resulted in 1037 reported poisoning cases. In 1969, analytical procedures were developed that allowed PCBs to be identified in concentrations of parts per million in environmental samples. In 1970, PCBs were identified as the contaminant in Coho salmon from Lake Michigan. The reproduction rate of commercial mink had been affected when they were fed contaminated salmon. The mink reproductive problems had first been reported in 1965; identification of PCBs as the cause awaited development of satisfactory analytical procedures.

In 1971, Monsanto voluntarily discontinued the sale of PCBs for all uses except totally enclosed electrical systems. In 1972, the U.S. Food and Drug Administration (FDA) established temporary tolerances for PCBs in food, and FDA surveillance resulted in the rejection of numerous lots of fish and occasional lots of chicken and eggs. By 1975, evidence of the presence of PCBs in industrial effluents and in the environment had been accumulated, and reports of PCB contamination were featured in the non-technical press. On March 26, 1976, Senator Gaylord Nelson of Wisconsin introduced into the Senate an amendment to the Toxic Substances Control Act (TSCA) which required the eventual elimination of the use of PCBs in the United States. This amendment was the basis of Section 6(e) of TSCA, and the eventual ban on the manufacture of PCBs became a legislated requirement on October 11, 1976, when TSCA was signed into law.

At the same time they were considering the PCB amendment to TSCA, the EPA proposed toxic pollutant effluent standards for PCBs under Section 307(a) of the Federal Water Pollution Control Act. The proposed regulation was published in the Federal Register on July 23, 1976; it proposed banning PCB discharges by any PCB manufacturer. It placed severe limitations on PCB discharges by capacitor and transformer manufacturers. Following extensive hearings, the PCB effluent standard was promulgated on February 2, 1977. The regulation required the elimination of discharges of PCBs by PCB manufacturers, transformer manufacturers, and capacitor manufacturers using PCBs by February 2, 1978. A one year compliance deadline for manufacturers of electrical equipment was allowed to enable plants to phase out the use of PCBs, convert to substitutes, make appropriate technological or process changes, or take such other steps as are necessary to achieve compliance.

Regulatory implementation of the various requirements of Section 6(e) of TSCA has occurred in several steps. EPA proposed regulations on the marking and disposal of PCBs on May 24, 1977. These regulations were promulgated on February 17, 1978. They establish labeling and disposal requirements for PCB material and equipment and require EPA approval of incinerators and landfills used for the disposal of PCBs. Additional regulations banning the manufacturing, processing, distribution in commerce, and use of PCBs were proposed by EPA on June 7, 1978. An analysis of the economic impacts of this proposed regulation was presented in a separate contractor's report published by the EPA.[2]

The action to ban the continued use of PCBs in the United States was not completely unexpected. PCBs were banned in Japan in 1972, and adequate substitutes were developed within a year or two. In 1972, Monsanto introduced a new PCB mixture, Aroclor 1016, which contained about 40 percent by weight chlorine and was marketed as a "more biodegradable PCB" for capacitors. General Electric Company, among other capacitor manufacturers, had been testing dielectric liquids for several years and announced the limited availability of non-PCB fluorescent light ballast capacitors late in 1976. The Dow Chemical Company developed a substitute for PCBs in large capacitors; the availability of capacitors using this dielectric fluid was announced late in 1976 by the McGraw Edison Company. By late 1977, all manufacturers of large power factor capacitors had discontinued the use of PCBs, and by late 1978, all small capacitors were being manufactured without PCBs.

PCBs have never been used in more than about five percent of all liquid-filled transformers, and substitute liquids having higher fire points than regular transformer oil were under test as early as 1974. Silicone dielectric fluid has been used for the same purposes as PCBs in both electromagnets and liquid-filled electric motors since the early 1970s. Railroad locomotives had been built in Japan using silicone liquid-cooled transformers in 1973 and were reported to operate satisfactorily.

Although a number of substitutes for PCBs have been developed during the past 5-10 years, sufficient time has not elapsed for experience to prove which, if any, of the materials will be satisfactory in each application. It

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(2) Versar, Inc., Microeconomic Impacts of the Proposed PCB Ban Regulations, Springfield, Va.: National Technical Information Service (Report No. NTIS PB-281-881/3WP), May, 1978.

is the purpose of the following sections to discuss the performance requirements for substitutes for PCBs and to evaluate the degree to which presently available materials meet these requirements. Because there are no materials available that are exact replacements for PCBs, alternative technologies for performing the functions previously filled by PCB equipment are also discussed.

No attempt has been made in this study to exhaustively investigate substitutes for PCBs. Much work is being done and is planned to meet the requirements mandated by the banning of PCBs. This work is reviewed where relevant. Thus, the following sections should be considered an in-depth status report rather than a comprehensive monograph.

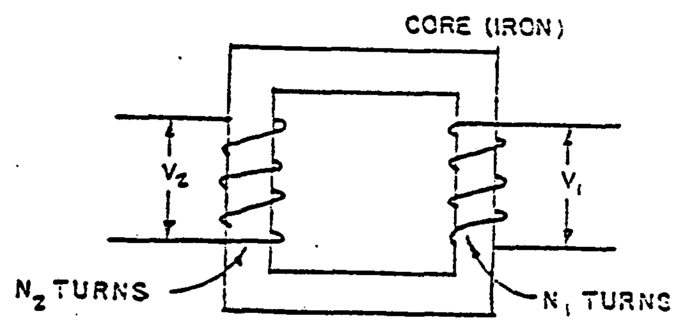
2.0 TRANSFORMERS

Polychlorinated biphenyls have been used as liquid coolants in electrical transformers located where fires might endanger human life and property. PCBs have the advantage of nonflammability in contrast to mineral oil, the other major liquid coolant used in transformers. Gaseous coolants are also nonflammable, but gas-cooled transformers have certain disadvantages when compared to liquid-cooled transformers. Dry type transformers are generally more expensive than the liquid-cooled units, and they usually have increased operating noise levels and a lower capacity of withstand temporary overheating caused by surges of power in the electrical circuit. Alternative liquid coolants are available but none have the fire resistance of PCBs. The following discussion includes a summary of the purposes of transformers in electrical circuits, heat generation in transformers, ideal heat transfer fluids for transformers, and the present status of substitutes for PCBs as transformer coolants.

2.1 The Use and Operation of Transformers

A transformer consists of two coils of wire connected magnetically by an iron core as shown schematically below. An alternating current applied to one winding (the primary winding) creates an alternating magnetic field in the iron core. This alternating magnetic field induces an electric current in the other, or secondary, winding. In a simple transformer, the ratio of voltages in the primary and secondary windings is equal to the ratio of turns in the windings, or

$$\frac{V_1}{V_2} = \frac{N_1}{N_2}$$



There are two types of transformers used in the electrical power industry: power transformers, used generally for "stepping up" voltage (e.g., at the power plant) and distribution transformers, used to "step down" voltages at or near the site of power use. The distinction between power and distribution transformers is actually not well defined. As will be seen below, some transformers used for voltage step-up are classed as distribution transformers and vice versa. However, whether a transformer is used for voltage step-up or step-down, the operating principle is the same: step-up transformers have a greater number of turns on the secondary winding, and step-down transformers have a greater number of turns on the primary winding. In theory, a step-up transformer can be converted to a step-down transformer by simply reversing the position of the transformer in the circuit.

A typical power plant generates about 1,000 megawatts, or a million kilowatts, which would be enough power to light 10 million 100-watt bulbs if none of the power generated at the power plant were lost in the transmission wires carrying the power to the bulbs. Since the wires carrying electricity from a power plant to the electrical loads in homes and factories offer resistance to the flow of electricity, a certain amount of energy must be expended to get the electrical power from the power plant to the home or factory. This lost energy — or power, since it is lost at some rate per unit of time — is radiated in the form of heat from the transmission wires. Transformers are used as one method of minimizing these transmission losses. The less the wires heat up, the less the amount of energy lost in the wires during the transmission of power.

The energy losses in a power transmission line (or simply, powerline) running from a power plant to a community of homes and factories are, as with the purely resistive loads, a product of the voltage difference between the ends of the powerlines (one end being at the power plant and the other being at the site of power use) and the amount of current being pushed through the powerline. However, the losses in a powerline can also be written as the product of the electrical resistance of the power line (measured in ohms) and the square of the current being carried in the lines so that

$$P = i^2R$$

where P is the power lost in the wire, i is the current, and R is the resistance of the wire.

Since the resistance of the wire can be minimized only by increasing the diameter of the wire (which is expensive because the wires are made of costly metals such as copper or aluminum), the best way to minimize power losses in the transmission wire is to minimize the current. In order to transmit power from the power plant to a community at a lower current, the voltage must be increased by the same factor by which the current is decreased. For example, if a 1,000-megawatt power plant transmitted its power at 120 volts, the current in the transmission wires would be more than 8 million amperes. If the transmission voltage were 120,000 volts, the current would be only about 8 thousand amperes. Since losses in the transmission wire are proportional to the square of the current, in the first case losses would be proportional to 8 million squared, or 64 trillion; the losses in the second case would be proportional to 8 thousand squared, or 64 million. The resistive power loss at the higher transmission voltage would be a million times less than if the power were transmitted at 120 volts.

The function of transformers used in power distribution is to transform electrical power from low-voltage and high-current characteristics to high-voltage and low-current characteristics, and then to transform it back to the relatively low voltage commonly used in homes. However, because transformers contain a great deal of current-carrying wire, a certain amount of electrical energy is lost in transformers. This energy loss manifests itself as heat. If the heat is not removed, the temperature of the transformer's electrical insulation might burn out, or the wire windings could short circuit and even melt. Therefore, electrical transformers must be kept cool so that they can operate reliably for long periods of time. They must also be kept cool because they operate more efficiently, i.e., with less energy loss, at lower temperatures.

Small transformers of the type found in radios and television sets are cooled by the thermal conduction of excess heat into the air around the transformer. When the air is warmed, it rises so that new, cool air is continuously brought into contact with the transformer. This is the reason for ventilation holes in television sets and radios; the holes allow the free flow of cooling air. In larger transformers used to step up the voltage at the power plant, or to step down the voltage near the site of use, use of air to cool the outer surface of the transformers may not remove heat rapidly enough from the middle of the transformer. There are many large air-cooled transformers in service, but they have certain disadvantages which are discussed below. Liquid-cooled transformers are the most common types; most are cooled with mineral oil, which is inexpensive but is flammable and can catch fire if the transformer undergoes an internal short circuit.

It is important to place the distribution (step-down) transformer as closely as possible to the point where the power is used to minimize transmission losses. Therefore, these transformers are often located in buildings or on the roofs of buildings where fires would constitute serious risks. For large transformers used in locations where transformer fires might endanger people, polychlorinated biphenyl formulations have been used as the cooling liquid because of their combination of fire resistance, low cost, and electrical properties.

Other common applications of PCB-filled transformers include:

Distribution transformers in electric generating stations to supply power to pumps and conveyors.

Step-up transformers used to generate high voltage electricity for electrostatic precipitators on tall stacks.

Railroad locomotive and transit car transformers where the power to the train is supplied as high voltage electricity from an overhead catenary.

2.2 Heat Generation in Transformers

Since the wires that carry electrical power from the site of generation (be it a battery or an electrical generator) to an electrical load also offer resistance to the flow of electrical current, a portion of the power generated is lost through heating of the wires connecting the load to the electrical power source. For a given wire diameter, electrical resistance is proportional to the length of the wire. In many circuits (e.g., an automobile electrical system), the power lost in the transmitting wires is small in comparison to the power delivered at the load (such as the headlights). However, in transmitting electrical power over long distances, the resistance of the wires could cause the dissipation of a significant portion of the energy intended for the load.

The wire in the transformer winding offers resistance to the flow of electricity and results in the production of heat in the windings. Since the electrical resistance of most conducting materials increases with temperature, the efficiency of the transformer (i.e., the ratio of the output power to the input power) is greatest when the transformer is kept at a low operating temperature.

The generation of an alternating magnetic field in the core material is never completely reversible. Not all of the energy stored in the magnetic field is recovered as electric power when the direction of the field is reversed; the lost power appears as heat. The magnetic field can induce electric currents in the core material as well as in the windings; these eddy currents are also dissipated as heat. Only the resistive losses are proportional to the load on the transformer. The total heat generated is typically 0.3 to 0.6 percent of the power passing through the transformer. Therefore, all transformers used in the electrical industry have provision for cooling with either gaseous or liquid coolants.

2.3 Desired Properties for Transformer Heat Transfer Fluids

The purpose of the heat transfer fluid in a transformer is to absorb the heat produced in the windings and core, to transfer the heat to cooling fins, and to provide electrical insulation within the transformer. The ideal fluid should have the following properties:

Thermal:

a. High heat capacity - able to absorb heat generated in the transformer during overload conditions with minimum increases in temperature.

b. Low viscosity - able to increase convective heat transfer and/or reduce pumping costs.

c. High coefficient of thermal expansion - able to provide good thermal siphoning action.

d. High thermal conductivity - able to maximize conductive heat transfer.

e. Low freezing point - able to withstand very cold temperatures (freezing could distort the coils and damage the transformer).

f. High boiling point - able to withstand at least maximum expected temperature. (A boiling point below that would require the use of a pressure vessel to prevent boiling and loss of fluid.)

Chemical:

a. Chemical stability when exposed to high temperatures and intense electric field for long periods of time in the presence of copper and other potential catalysts.

b. Non-flammability in the event of a spill.

c. Non-flammable degradation products in the event an electrical arc occurs inside the transformer.

d. Non-corrosive degradation products formed by arcing.

e. Low solvency toward other materials of construction.

Electrical:

a. High dielectric strength - the liquid acts as an electrical insulator filling any cracks that develop in solid insulation.

b. High resistance to corona formation.

c. Low loss tangent to minimize dielectric heating of the liquid.

d. Minimal degradation of electrical properties if contaminated with moisture.

Toxicity:

a. Non-toxic - both acute and chronic.

b. Biodegradable.

c. Non-toxic degradation products - from biodegradation, arcing, and fires.

Cost: Low Cost.

Availability: Multiple sources with standard and reliable properties.

2.4 Use of PCBs in Electrical Transformers

The most commonly used non-flammable transformer coolant liquids have been mixtures of PCBs known as askarels. Askarel is defined by the National Electrical Code as "a generic term for a group of non-flammable synthetic chlorinated hydrocarbons used as electrical insulating media. Askarels of various compositional types are used. Under arcing conditions the gases produced, while consisting predominantly of non-combustible hydrogen chloride, can include varying amounts of combustible gases depending on the askarel type."

The most commonly used askarel compositions are Inerteen (Westinghouse trade name for 70 percent PCB mixture prior to 1968, 100% Aroclor 1242 since 1968) and Pyranol (General Electric trade name for 70 percent mixture). The exact composition of both Pyranol and Inerteen have been changed from time

TABLE 2.4-1

MAJOR TRADE NAMES AND PRODUCERS OF TRANSFORMER ASKAREL

TRADE NAME	MANUFACTURER
Asbestol	American Corporation
Chlorextol	Allis-Chalmers
Inerteen	Westinghouse Electric
No-Flamol	Wagner Electric
Pyranol	General Electric
Saf-T-Kuhl	Kuhlman Electric

to time. Table 2.4-1 lists trade names and producers of various askarel formulations. Prior to the mid-1950's, the insulating liquid used in many transformers (General Electric formulation) was a 50-50 mixture of Aroclor 1260 (60 percent chlorine) and tri-chlorobenzene. In the late 1950's, the chloro-benzene component was changed to a mixture of tri- and tetrachlorobenzenes. In September 1971, at Monsanto's suggestion, the Aroclor component was changed to Aroclor 1254 (54 percent chlorine). The most recent Westinghouse formulation (Inerteen) used Aroclor 1242 (42 percent chlorine).

The volume of askarel used in transformers ranges from 3 to 3,400 gallons (33 to 38,000 lbs), with an average of about 230 to 320 gallons (2,500 to 3,500 lbs). About 135,000 to 140,000 transformers using PCBs have been put into service since 1932. These units represent about 15 percent of all large transformers in service. Virtually all askarel transformers are still in service. The production rate of askarel transformers until recently was about 5,000 units per year, requiring some 10 to 15 million lbs of PCBs.(1)

One manufacturer of askarel transformers classified its production in this manner:

Power transformers:

a. Railroad transformers used on board electric locomotives or multiple unit electric railroad cars. (Receive up to 25,000 volts and contain 700 to 2,400 lbs of askarel in each unit depending on the rating and size of the transformers.)

b. Furnace transformers used in proximity to glass melting and induction furnaces, which require high-current, low-voltage power supplies. (Receive up to 15,000 volts and contain 2,000 to 4,000 lbs of askarel.)

c. Rectifier transformers used for large rolling mills and DC industrial power supplies. (Receive up to 15,000 volts AC and deliver low-voltage high-amperage D.C. Each unit contains about 19,000 lbs of askarel.)

d. Shunt reactors, which provide reactance. (Receive up to 15,000 volts under normal operating conditions and deliver voltage and current as received.) The purpose of shunt reactors is to suppress voltage rise at light loads, control output voltage, and generally to act as an electric governor.

e. Grounding transformers. (Receive up to 15,000 volts.)

Distribution Transformers:

a. Secondary unit substation (Receive up to 15,000 volts and deliver less than 1000 volts.)

b. Pad-mounted (Receive up to 14,400 volts and deliver 120, 240, and 480 volts.)

c. Pole-mounted (Receive up to 14,400 volts and deliver 120, 240, and 480 volts.)

d. Precipitator power supply (Receive 480 A.C. volts and deliver 56-60 kilovolts low-amperage D.C.)

Quantities of askarel used in these distribution transformers are usually in the range of 3 to 400 gallons in each unit depending on the rating and the size of the unit.

The service life of an askarel transformer is expected to be greater than 30 years. The failure rate for transformers presently in service is about 0.2 percent per year. Only 1 percent of these failures actually results in rupture of the transformer casing, so the total uncontrolled loss is probably less than 8000 lbs out of about 420 million lbs of askarel in transformer use.

Obsolescence of existing transformers is 1 to 2 percent per year. Obsolete transformers are moved to new locations or sold on the used equipment market, or the askarel may be reclaimed and sold for transformer maintenance.

Liquid coolants in transformers have better heat transfer and heat capacity characteristics than gaseous coolants. PCBs have the additional advantage of being non-flammable. The other advantages of PCBs are their high dielectric strength, outstanding chemical stability, relatively low viscosity, and low freezing point. The chemical stability of PCBs assures reliable transformer performance without frequent maintenance. On the other hand, oil-filled transformers require a great deal of maintenance. Naphthenic base mineral oil gradually decomposes resulting in the formation of sludge, which interferes with transformer heat transfer. The decomposition also degrades the electrical properties of the mineral oil. This reaction is accelerated if the oil is exposed to air. Therefore, it is common practice to test the properties of oil in oil transformers every year or two and to treat or replace the oil if it has degraded. PCBs are also subject to degradation of electrical properties if minor arcing occurs in the transformer or if moisture is absorbed from air leaking through faulty busings or gaskets. However, the rate of degradation of PCB is usually less than that of transformer oil, and routine testing of PCB transformers is conducted less frequently than for oil-filled units.

Disadvantages to PCBs, in addition to the environmental threat, toxicity, and pungent smell, were cost (about eight times as much as mineral oil, on a volume basis) and the highly corrosive HCl they produce if arcing occurs in a transformer.

Most askarel-filled distribution transformers are located inside public, commercial, or industrial buildings or are mounted on the roofs of such buildings. No special enclosures or vaults are required except as are necessary to prevent accidental electrical or mechanical contact with the equipment. However, the National Electrical Code does specify vaults for the indoor installation of PCB-filled transformers rated at more than 35,000 volts. Askarel-filled transformers are limited by the dielectric strength of the liquid to ratings below 69,000 volts.

Most power transformers are situated in remote locations where a fire or an explosion would not be a threat to property. Mineral oil is usually used in power transformers installed in these safe locations. However, some utilities use askarel-filled power transformers at generating stations.

Step-up transformers are used to supply high voltage electricity to electrostatic precipitators. These units are usually mounted on or very near the small stack. This minimizes the problems associated with the in-plant distribution of high voltage power. These transformers are usually askarel filled to minimize fire hazard in the crowded area of the stack and to reduce the requirement for routine monitoring of oil properties of these rather inaccessible transformers.

Railroad equipment powered by high voltage A.C. power from overhead catenaries is used in the U.S. Northeast Corridor. Askarel-filled transformers are mounted in engines and under self-propelled passenger cars to reduce the catenary voltage to that required by the traction motors. The primary use of this equipment is in passenger service on the Northeast AMTRAK routes and on the commuter lines around Philadelphia and New York. A total of 1009 askarel-filled transformers are in use in rolling stock including the old GG-I locomotives, in the Metroliner cars, in various commuter cars and in the new E-60 locomotives. (Twenty-six E-60 locomotives were built for AMTRAK by General Electric about three years ago; each locomotive contains 710 gallons of askarel.) Conrail (formerly Penn Central) operating rules have required the use of askarel transformers in all cars and locomotives using the tunnels and stations in New York. This fire safety rule was established after an early GG-I locomotive containing a mineral-oil-filled transformer caught fire just outside an entrance to a tunnel early in the 1940's.

2.5 Alternatives to the Use of PCBs in New Transformers

The installation of transformers in office buildings, apartment buildings, and factories is governed by local regulations which are generally based on the provisions of the National Electrical Code (NEC). The NEC is incorporated by reference into OSHA regulations and therefore applies to all workplace transformer installations except in electric utilities, railroads, and mines.

Prior to the publication of the 1978 NEC, the only types of transformers recognized by the code were askarel transformers, dry type transformers, and oil-insulated transformers. Installation requirements were specified for each type depending on whether the transformer was located inside or outside a building. The 1978 NEC defines a new type of transformer, "high fire point liquid insulated transformers," for use as an alternative to askarel transformers. Installation requirements for these transformers are summarized in Table 2.5-1.

The Toxic Substances Control Act (TSCA) of 1976 established an eventual ban on the manufacture of transformers containing PCBs. In anticipation of the restrictions on PCBs, all transformer manufacturers except one ceased production of askarel transformers by mid 1977. The remaining manufacturer anticipated the cessation of production by the end of 1977.

The choice among the available types of non-PCB transformers will depend upon availability, technical suitability, and total installed cost for each installation. Consideration should also be given to fire safety, efficiency, toxicity, and environmental acceptability for each type of non-PCB transformer. The following sections summarize the advantages and potential disadvantages of using various substitutes for PCB-filled transformers.

2.5.1 Non-PCB Askarels

In the past, askarels have consisted primarily of complex mixtures of PCBs diluted with lesser amounts of chlorinated benzenes. There is no requirement in the definition of askarel for the inclusion of any PCBs in the mixture. Therefore, it is possible to formulate askarels from chlorinated hydrocarbons without using PCBs.

Table 2.5-1*

Installation Requirements for Electrical Transformers

Type	Location: Indoors	Location: Outdoors
Askarel		
< 25 KVA, < 35,000 V	No vent or vault required	No requirements
> 25 KVA	Pressure relief vent and outside venting required	No requirements
> 35,000 V	Vault required	No requirements
High Fire Point Liquid		
< 35,000 V	Catch basin required	No requirements
> 35,000 V	Vault required	No requirements
Dry Type		
< 112 1/2 KVA, < 600 V Completely enclosed	No requirements	Weather proof enclosure required
< 112 1/2 KVA, < 600 V Not completely enclosed	Separated from combustible material by at least 12" or by a fire-resistant heat-insulating barrier	Weather proof enclosure required
> 112 1/2 KVA, < 35,000 V	Install in fire-resistant transformer room (exceptions for totally enclosed, ventilated transformers, and transformers with 80°C rise installation)	Weather proof enclosure required
> 35,000 V	Vault required	Weather proof enclosure required
Oil-Insulated		
< 600 V, < 10 KVA	Catch basin required	Diked floor and/or sprinklers required for roof mounted and other hazardous locations
< 600 V, < 75 KVA	Catch basin required	
< 112 1/2 KVA	4" thick concrete vault required	
> 112 1/2 KVA	Transformer vault required	

*National Fire Protection Association, National Electrical Code 1978, Boston, Ma.:1977, Article 450, Section B.

There have reportedly been a number of askarel transformers recently built in Canada that use as a coolant liquid an eutectic mixture of tri- and tetra-chlorobenzenes with no PCBs. This mixture results in a non-flammable liquid that meets the definition of Prodelec (France). This material is reportedly a mixture of 1,2,3 trichlorobenzene, 1,2,4 trichlorobenzene, 1,2,3,4 tetrachlorobenzene, and 10% to 20% terphenyl; it is being marketed in the U.S. by GE under the trade name Iralec.

Use of straight chlorinated benzenes as a coolant may require changes in the design of askarel transformers. The most important difference is in the choice of materials; the straight benzene askarel mixtures have a greater solvency than askarels based on PCBs, and different insulation, gaskets, and enamels may be required. The use of paper as a wire insulation would result in an increase in the size and weight of the transformers. The freezing point of the chlorinated benzene mixture used in Canada is about $9^{0}C$, so the transformers must be shipped in the summer and protected against freezing after installation. If the liquid were to freeze, it could distort the coils in the transformer. Significant distortion could cause transformer failure. Presence of the hydrocarbon material in the Prodelec mixture would be expected to widen the freezing range and reduce the danger of distorting the transformer windings.

A change to a mixture of chlorinated benzenes would not result in any significant supply problems. According to a recent study, the 1973 U.S. production of 1,2,4 trichlorobenzene was over 28 million pounds and the 1973 production of 1,2,4,5 tetrachlorobenzene was over 18 million pounds.[(3)] The use of 1,2,4 trichlorobenzene as a functional fluid (a use category including askarel) in 1975 was about 5 million pounds.

(3) West, W.L. and S.A. Ware, (Ebon Research Systems), Investigation of Selected Environmental Contaminants: Halogenated Benzenes — Draft Report, Washington, D.C., Office of Toxic Substances, USEPA, March 1977.

Chlorinated benzenes are extensively used in industry, and considerable quantities are entering the environment. Because of their toxicity, environmental stability, and potential for bioaccumulation, all of the chlorinated benzenes have been included on the Interagency Testing Committee's Priority List of chemical substances recommended for testing under Section 4 of the Toxic Substances Control Act. The chlorinated benzenes are also listed as toxic pollutants under Section 307(a) of the Clean Water Act.

Chlorinated benzenes present less of an environmental problem than PCBs. An evaluation of these materials should compare their health effects, their environmental distribution, and their environmental fates to those same characteristics in other available substitutes for PCBs. Chlorinated benzenes are quite volatile; their use in a transformer located indoors would require that the transformer be vented outside the building. Such venting would eliminate high concentrations of vapor inside the building resulting from arcing within the transformer. Inhalation has been found to be the major entry path of paradichlorobenzene into the human body. This is probably also true for tri-chlorobenzen. A recent study of the presence of chlorinated compounds in humans found that people in the Tokyo Metropolitan area had three times as much dichlorobenzene in their blood as PCBs. Concentrations within adipose tissue were the same for PCBs and dichlorobenzene.[4] This result is due both to the greater tendency of PCBs to accumulate in fatty tissue and to the ability of the body to metabolize and excrete chlorinated benzene. Even tetrachlorobenzene is slowly metabolized and excreted. A test with rabbits indicated that only 10% remained in the body after six days. It was determined that 43% of the ingested tetrachlorobenzene was converted to 2,3,4,5-tetrachlorophenol prior to excretion and that the remainder was excreted intact.[5] The metabolism of tetrachlorobenzene is accompanied by significant changes in liver function at exposures considerably below the LD_{50} dosage, and is estimated at 1500 mg/kg (rats) and 1035 mg/kg (mice).[6] The single oral

(4) Morita, M. and G. Ohi, "Paradichlorobenzene in Human Tissue and Atmosphere in Tokyo Metropolitan Area," Environ. Pollut., 8, 1975.
(5) Jondorf, W.L., et al., "Studies in Detoxication — The Metabolism of Halogenobenzenes. 1:2:3:4-, 1:2:3:5- and 1:2:4:5-Tetrachlorobenzenes." Biochem. Jour. 69:181, 1958.
(6) Fomenko, V.N., "Determination of the Maximum Permissible Concentrations of Tetrachlorobenzene in Water Basins," Hyg. Sanit. 30:8, 1965.

acute LD_{50} for 1,2,4-trichlorobenzene has been estimated to be 756 mg/kg.[7]

2.5.2 High Fire Point Transformer Liquids

The 1978 edition of the National Electrical Code added a new specification for high fire point liquid insulated transformers. Coolant liquids meeting these specifications must have a fire point of at least 300°C, must not propogate flames, and must be approved.

A number of methods for evaluating the relative fire safety of high fire point transformer liquids have been developed by Factory Mutual Research. This work was performed under a research program sponsored by the transformer committee of the National Electrical Manufacturers Association. Because test protocols are incomplete, Factory Mutual has not formally approved any liquids as "high fire point transformer liquids." However, they have given tentative acceptance to a number of commercially available liquids based on silicones, synthetic hydrocarbons, and paraffinic hydrocarbons. Acceptance means that Factory Mutual recommends that insurance companies insure facilities where high fire point liquid-filled transformers containing accepted liquids are installed in accordance with the requirements of the National Electrical Code. However, the insurance company reserves the right to require additional fire protection at a later time if such a need is demonstrated by experience.

Formal approval requirements have not yet been established by Factory Mutual, but draft approval requirements are in the process of review by the standards group. The suggested criteria would require (a) that transformers filled with approved less flammable liquids be installed in a diked area where the diked volume is sufficient to contain all of the liquid and (b) that the diked area be drained to a safe location if this is feasible. Any approved liquid having a fire point above 300°C could be used in transformers in flammable buildings having sprinkler systems. In build-

(7) Brown, V.K.H., "Acute Toxicity and Skin Irritant Properties of 1,2,4-Trichlorobenzene," Ann. Ocup. Hyg. 12:209, 1969.

ings of noncombustible construction (without sprinklers), the minimum allowable ceiling height over a high fire point liquid-filled transformer would be based on the heat release rate of the particular liquid used in the transformer. The heat release rate used in this calculation would be measured for each liquid in a test involving a burning quiescent pool of standard size, temperature, and ignition source.

The properties of the liquids presently accepted by Factory Mutual are summarized in Table 2.5.2-1 as abstracted from manufacturers' literature. The major contenders for this market at present are the dimethyl silicones and the RTEmp parafinic hydrocarbon. The silicone dielectric is more costly, but it has a lower heat of combustion than RTEmp. The importance of the heat of combustion of a non-propogating liquid is also being investigated by the National Bureau of Standards under a program sponsored by the U.S. Department of Energy.

There are a number of questions not yet satisfactorily answered concerning the use of the high fire point transformer liquids. The most important question is: how realistic are the test conditions? It has been suggested that catastrophic arcing followed by case rupture is a relatively unusual mode of transformer failure and that a more frequent problem is prolonged minor arcing which generates flammable gases caused by the breakdown of transformer fluid. Because of flammability of these gases, tests based on the flash point or flammability of unused liquids may not be reliable indications of their relative fire safety under actual transformer operating conditions.

2.5.3 Oil Insulated Transformers

If fire safety were not a consideration, oil-filled transformers could be used in all applications. Askarel transformers historically cost about 1.3 times more than oil-filled units of the same capacity. As the result of costs, most users have preferred to use the oil type unit where possible. The oil filled transformers are the same size as the askarel units and are considerably lighter in weight. Furthermore, mineral oil has somewhat better heat transfer characteristics than askarel, and an electrical arc in mineral oil

Table 2.5.2-1

High Fire Point Transformer Liquids

Type of Liquid	Silicone	Hydrocarbon	Synthetic Hydrocarbon
Chemical Composition	Polydimethyl siloxane $-[Si(CH_3)_2O-]_n-$	Paraffinic oil refined from crude oil $-(CH_2)_n-$ plus additives	Poly alpha olefins $-(CH_2)_n-$
Commercial Products	DC 561 - Dow Corning DC 200 - Dow Corning SF 97 - General Electric L 305 - Union Carbide F 101 - SWS Silicones F 190 - SWS Silicones	RTEmp - RTE Corp.	FR Dielectric Fluid - Gulf Oil Chemicals Co. PAO-13CE - Uniroyal Chemical
Dielectric Constant ASTM D-924	2.72	2.38	2.11 (FR) 2.11 (PAO-13CE)
Dielectric Strength ASTM D-877, ASTM D-1816	35 KV (45 KV at 50 ppm water) guarantee	43 ± 2 KV	46 KV (FR) 39 KV (PAO-13CE)
Resistivity ohm-cm ASTM D-1169	7.1×10^{14}	8×10^{12}	7×10^{14} (FR) 6×10^{15} (PAO-13CE)
Dissipation Factor ASTM D-924	1.8×10^{-5} (100 hz, 23°C)	1×10^{-5} (25°C)	2×10^{-5} (FR) 1×10^{-6} (25°C) (PAO-13CE)
Flash Point	~ 300°C	285°C	298°C (FR) 290°C (PAO-13CE)
Fire Point	~ 360°C	312°C	320°C (FR) 307°C (PAO-13CE)
Heat of Combustion	7.67 kcal/gram	11.0 kcal/gram	10 kcal/gram (FR)
Pour Point	- 55°C	- 30°C	- 45°C (FR) - 44°C (PAO-13CE)
Arc Decomposition Products	Hydrogen, methane, amorphous silica May form CO on burning	Hydrogen, methane, some higher hydrocarbons May form CO on burning	Hydrogen, methane, some higher hydrocarbons May form CO on burning
Specific Heat	.34	.46	.42 (FR)
Coefficient of Expansion (1) cc/cc°C	.00104	.00085	.00081 (FR) .00075 (PAO-13CE)
Specific Gravity	.961 (25°C)	.876 (25°C)	.857 (FR) .84 (PAO-13CE)

Table 2.5.2-1, (Continued)

High Fire Point Transformer Liquids

Viscosity - CS[2] 25°C 100°C 150°C	 50 16 12	 350 16 5.5	PAO-13CE FR ? 87 (38°C) 14 11 ? ?
Corrosivity	Not corrosive to normally used transformer materials	Not corrosive to normally used transformer materials	Not corrosive to normally used transformer materials
Solvency	Swells silicone rubber, may leach plasticizers from plastics causing shrinkage and hardening.[3]	Swells butyl rubber, no effect on most materials	Swells butyl rubber, no effect on most materials.
Acute Toxicity Oral	Non toxic[4,5] LD_{50} > 28 gm/kg	Non toxic LD_{50} > 10 gm/kg[6] May contain up to 2% non-paraffinic additives, including aromatic compounds	Non toxic LD_{50}(rats) > 40 ml/kg (PAO-13CE)
Inhalation	Non toxic[4]	Long term exposure limit = 5 mg/m^3 (Note - higher than can be achieved under normal mfg or use conditions)	
Dermal	Non irritating[4]	No dermal effects identified in industrial hygene survey(5)	No skin irritations after 72 hour exposure - rabbit (PAO - 13CE)
Eye Contact	Very slight and transient irritation.[5]	Very slight and transient irritation[5].	No ocular reactions observed - rabbit (PAO - 13CE)
Chronic Toxicity	47 gm/kg/day - no toxic effect (guinea pigs) 20 gm/kg/day - no toxic effects (rats) FDA allows polymethyl siloxanes as food additives up to 10 ppm	Not tested	
Mutagenicity	No effects noted[4]	Ames test did not show any affect of chemical in either pure or rat liver activated cultures (PAO-20E)	Ames test did not show any affect of chemical in either pure or rat liver activated cultures (PAO- 13CE) (FR)

Table 2.5.2-1, (Continued)

High Fire Point Transformer Liquids

Carcinogenicity	No effects noted[4]	Non carcinogenic[6] based upon mutogenicity testing.	
Bioaccumulation	Low[4]	Low[6]	Low
Biodegradation	Does not biodegrade[4]	Biodegradable[6]	Should be very biodegradable
Environmental Fate	Stable in environment; may eventually decompose to silica on activation by UV light[4]	Degraded to water and carbon dioxide	Degraded to water and carbon dioxide
Ultimate Disposal	Incineration[7]	Incineration[7]	Incineration[7]
Experience in transformers		Used since 1970	Field tests started recently
Cost	~ 12.00/gal-large quantities ~ 15.00/gal-small quantities	6.90/gal 4500 gal bulk shipment 8.35/gal 5 gal. can	7.00/gal-tank truck lot 7.75/gal-55 gal drum PAO-13CE (Oct '78)

Notes for Table 5.2.1-1 on following pages.

NOTES: Table 2.5.2-1

1. All liquid-filled transformers contain a vapor space that is filled with nitrogen gas. The increased pressure due to thermal expansion of the liquid depends both on the volume of the vapor space and the solubility of nitrogen in the liquid. Tests reported by Dow Corning indicate that the pressure rise in operating transformers is about the same for both liquids even though the silicone expands more.[8]

2. Most transformers depend on natural convection to circulate the dielectric liquid between the core and the cooling fins. The efficiency of the convective cooling depends on the change in density of the fluid over the range of temperatures experienced and on the viscosity of the fluid over this temperature range. The silicones have a greater coefficient of thermal expansion than the hydrocarbon liquids, but they also have a higher viscosity at temperatures above 100°C. Since the limiting factor in transformer life is the maximum hot spot temperature, which controls the rate of degradation of the solid dielectric material, the performance of the liquid coolant at the maximum temperature is perhaps more important than the average liquid temperature. At the maximum temperatures found in a transformer, the hydrocarbon liquids would be expected to have a lower viscosity than the silicones, but this lower resistance to convection is offset at least in part by the lower thermal expansion of the hydrocarbons which results in a lower driving force for convection. In general, both silicones and the hydrocarbon oils are less effective coolants than askarel, although changes in the design of new transformers can compensate for this difference. Preliminary tests have indicated that paper insulation degrades less rapidly in both silicone and hydrocarbon liquids than in askarel, perhaps due to the absence of acid

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(8) Page, William C. and Terry Michand (Dow Corning Corp.), Development of Methods to Retrofill Transformers with Silicone Transformer Liquids, Technical Paper presented at 1977 EEI Conference.

NOTES: Table 2.5.2-1 (Continued)

degradation products. Therefore, transformer life might not be significantly reduced even if the non-askarel liquid operates at somewhat higher temperatures than would be experienced with askarel.

3. Hurley, J.S. and A. Torkelson, (General Electric Co.), "Silicone Dielectric Fluids for Liquid Filled Transformers," IEEE Paper C-74-264-8, Jan. 27, 1974.

4. Summaries of health, environmental, and fate effects of silicones:

   Howard, P.H., P.R. Durkin and A. Hanchett, (Syracuse University Research Corp.), Environmental Hazard Assessment of Liquid Siloxanes (Silicones), Washington, D.C., Office of Toxic Substances, U.S. Environmental Protection Agency (Report No. EPA-560/2-75-004), September, 1975.

   Calandra, J.C. et al., "Health and Environmental Aspects of Polydimethylsiloxane Fluids," Polymer Preprints, 17(1), 12, April 1976.

5. Toxicity of Combustion Products of Polydimethyl Siloxane

   The products of complete combustion of polydimethylsiloxane are water, carbon dioxide, and amorphous silica. Some of the silica is present in the smoke as finely divided particles, and the balance remains as a solid on the surface of the burning silicone fluid. Incomplete combustion of silicone fluids produces methane, carbon monoxide, and hydrogen in addition to the previously mentioned compounds.[9]

   The toxicological effects of amorphous silica are of more concern than those of the other combustion products. OSHA is presently in the process of setting new exposure standards for amorphous silica. The present OSHA standard limits workplace exposure to 80 $mg/m^3/\%\ SiO_2$ and is based on the results of tests run with amorphous silica in the form of diatomaceous earth. Diatomaceous earth generally contains small amounts of crystalline silica which is a known cause of silicosis. The industry contends that the

(9) Burrow, R. F. and T. Orbeck (Dow Corning), Performance of Silicone Fluids as Insulating Liquids for High-Voltage Transformers, Doble Engineering Client Conference, Boston, Mass., April 22-24, 1974.

NOTES: Table 2.5.2-1 (Continued)

presence of crystalline silica in diatomaceous earth produces biased test results which implicate amorphous silica. The industry has submitted additional test results which indicate that the chronic toxicity of amorphous silica, uncontaminated with crystalline silica, is very low and that any lung damage caused by inhalation of amorphous silica particles reverses itself after exposure ceases.[10, 11] A NIOSH study entitled "Comparative Chronic Inhalation Studies of Synthetic Amorphous Silica" is currently in progress and should resolve this issue.

A study of the reports available indicated that short-term inhalation of smoke from the combustion of polydimethylsiloxane would probably cause no lasting effects attributable to the products of combustion.

6. Piotrowski, Margaret (RTE Corporation), Toxicity and Environmental Impact of Askarel Substitutes, Waukesha, Wisc.: RTE Corp., Sept. 23, 1977.

7. All of the high fire point liquids can be ultimately disposed of by incineration. The hydrocarbons could be easily added to residual fuel oil and burned in industrial boilers. The silicones, however, would yield considerable amounts of amorphous silica which could present a problem in contributing to stack gas opacity.

(10) Sarnac Laboratories, Regarding the Biological Activity of Hi-Sil Dust 101, New York: December 21, 1950.

(11) Schepers, G.W.H., The Biological Action of Inhaled Submicron Amorphous Silica: Hi-Sil 233, Ann Arbor, Michigan: University of Michigan, April 30, 1958.

results in breakdown products that are non-corrosive. Compared to high fire point liquid-filled transformers, the oil-filled transformers should be cheaper, lighter, smaller, and operate at lower temperatures.

Flammability. The major disadvantage to mineral oil is flammability. Transformer mineral oil has a flash point of 145°C, and if an arc occurs within the transformer, the breakdown products will be hydrogen and methane, both of which are flammable. Detailed records of such failures are maintained by the electrical industry.[12] Where oil-filled transformers are not specifically prohibited as on-site replacements for askarel-filled units, the National Electrical Code imposes certain restrictions on their mode of installation. (See Table 2.5-1)

Oil-filled transformers are used in almost all power transformer applications and for most substation distribution applications where the high voltage from the transmission lines is reduced to 12.8 kv for local distribution. Most pole-mounted transformers that reduce the voltage to 220 volts are also oil-filled. The issue of flammability becomes important if a distribution transformer must be buried (as in many urban applications) or located close to, within, or on the roof of the building it serves. An oil-filled transformer can be used in these applications only if it is suitably isolated from flammable structures or if these structures are suitably safeguarded against fires.

When a transformer is located outside the building it services, the low-voltage power must be brought into the building via cables or insulated buses, incurring additional energy losses caused by heating of the longer low-voltage transmission lines. For large buildings such as tall office buildings or large shopping centers or for heavy loads such as electric furnaces, the cost of these losses of electrical energy can easily exceed the higher cost of installing the transformer nearer the loads.

(12) Edison Electric Institute, Report on Power Transformer Troubles, Publication No. 71-20, 1971.

Vaults. The installation of oil-insulated transformers in buildings must comply with local electrical and building codes. These codes are usually based on provisions of the National Electrical Code (NEC). The NEC requires that all oil-filled transformers, except small low voltage units, be installed in fire resistant vaults with the following exceptions (NEC: Section 450-24):

1. If the total capacity of the transformer does not exceed 112-1/2 KVA, vault walls need only be 4 inches thick instead of 6 inches as specified in Section 450-42.
2. Where voltage does not exceed 600, a vault shall not be required if suitable arrangements are made to prevent a transformer oil fire from igniting other materials.

Sections 450-43 through 450-47 of the NEC give detailed specifications for vault doors, ventilation, drainage, pipe, and ductwork. Vaults in buildings are constructed as integral parts of the buildings. Accordingly, the costs of such vault construction cannot be easily estimated since the presence of a vault affects building design (i.e., strength of the supporting structure). Further, vault construction is performed as part of the general construction of the building. Transformer vault construction is so costly that very few oil insulated transformers have been used in buildings. Cost estimates based on a standard 1000 KVA 15 KV transformer indicate that the cost of the vault would be 133% of the transformer, compared to a 75% premium for an askarel transformer installed with a catch basin and outside vent.[13] Oil insulated transformers may be located adjacent to build-

(13) Westinghouse, Is There Another Way?, Sharon, Pa.

ings if adequate safeguards for fire protection are installed. In many urban areas, precast concrete manholes are used to house transformers in underground vaults adjacent to the buildings they serve. The steel gratings in the sidewalks of downtown areas are often the vent openings for transformer manholes.

Availability. Transformer oils currently used are naphthenic base materials. Although there are no problems with the present supply of this special grade of oil, it is likely that naphthenic crude oils will be in short supply by 1985. To overcome possible future shortages of suitable transformer oils, the Electric Power Research Institute is funding studies by the Westinghouse Research and Development Center, the McGraw-Edison Company, and General Electric Company. The purpose of these studies is to evaluate the performance of paraffinic-base transformer oils with heat transfer properties comparable to presently used oils.(14) Tests are being performed to compare various properties of the two types of oil including lubricity, gasing tendencies, oxidation stability, material compatibilities, aging at elevated temperatures, corona and high-current arcing characteristics, and simulated transformer performance. In addition, General Electric is reviewing future availability of insulating fluids. GE has reported that the paraffinic oils, which have been processed to reduce the temperature of wax formations to below -40°C, compare favorably with the presently used naphthenic oils and that no significant supply problems for paraffinic oils are anticipated.(15)

2.5.4 Air Insulated Dry Type Transformers

The operating life of any transformer depends on the rate of degradation of the insulation on the windings. The standard organic insulations

(14) Dougherty, John J., "R&D Status Report, Electrical Systems Division," EPRI Journal, November 1977, p. 45.

(15) Rouse, T.O. (General Electric Co.), "Evaluation of Alternate Mineral Oils for Use in Transformers and Other Electrical Apparatus," Conference Record of 1978 IEEE International Symposium on Electrical Insulation (78CH1287-2-EI), Piscataway, N.J.: IEEE Service Center, 1978.

that have been used for many years, such as paper and fabric, have performed satisfactorily when limited to the standard temperature rise of 65°C set by ANSI C57.12.10-1977. Liquid cooling, either convective or forced, has been used to ensure that this temperature rise is not exceeded.

The development of insulations based on glass, nomex, and high temperature potting compounds has allowed the design of transformers with a 220°C temperature limit. These transformers can be designed for operating with direct air cooling of the coils which eliminates the requirement for liquid coolants. Although the design of an air-cooled transformer sacrifices certain desirable properties, the SC units are cost competitive with oil-filled transformers on a first-cost basis where the oil-filled units must be installed in a vault.

Open Conventional Wound Transformers. Open coil air-cooled transformers are available in sizes up to 750 KVA in single-phase and 5,000 KVA in 3-phase units and are therefore generally available as alternatives to oil-filled transformers where a vault would be required for the oil-filled unit. Complete specification of air-cooled transformers must consider many details as summarized in the specification guide prepared by Lazar.[16] The major factors that must be considered in choosing between oil-filled and air-insulated transformers include:

Vault requirements. Oil-filled transformers above 112 KVA must be installed in 6-inch thick concrete vaults. Dry air-cooled transformers above 112 KVA must be installed in a "transformer room of fire resistant construction."

Voltage. Liquid-filled transformers below 600 volts do not require vaults. Dry air-filled transformers are limited to a maximum of 34,500 volts because air is a poorer electrical insulator than liquid.

(16) Lazar, Irwin (The Heyward-Robinson Co.), "Making the Choice Among Dry, Liquid, and Gas Transformers," Specifying Engineer, June, 1977, pp 92-96.

Basic Impulse Level (BIL): This is the voltage at which the insulation breaks down resulting in internal arcing. A high BIL provides additional protection against transformer failures caused by transient high voltage from lightning strikes and switching surges. Dry air-cooled transformers have Basic Impulse Levels 25 to 50 KV lower than liquid-filled transformers, although ratings up to 150 KV are available as an option. The lower resistance to transient voltages requires that more attention be given to proper sizing of lightning arrestors installed with dry transformers.

Overland Characteristics. The coolant in a liquid-filled transformer provides a heat sink which absorbs heat generated when a transformer operates at greater than design loads. Liquid-filled transformers are designed for normal coil temperatures of 55°C above ambient at full load conditions and have insulation rated at 120°C. This 40°C allowable temperature increase, together with the heat sink provided by the oil, allows liquid-filled transformers to operate at 200% of rated capacity for one half hour.

Dry transformers are designed for either 80°C or 150°C normal temperature rise and have insulating systems good to 220°C. The lack of the heat sink provided by oil results in more rapid temperature buildup during overload operating conditions. Although an 80°C temperature rise transformer will be better able to handle temporary overloads than a 150°C transformer, both types of dry transformer are limited when compared to liquid-filled units. Therefore, if widely fluctuating loads are encountered, dry transformers must often be specified 20% to 30% larger (in KVA rating) than liquid-filled units to ensure comparable operating life.

Efficiency. Energy losses occur in a transformer due to both hysteresis losses in the core and resistance heating of the windings. The amount of loss is a function of many different design factors. The lower temperature rise in an 80°C temperature rise winding vs 150°C winding is achieved by using larger wire and thereby reducing resistance losses. The effect of these energy losses on the economics of transformer loss and operation was recently discussed in an article by Frank.[17] Since load losses and total losses are a result of design choices resulting from economic trade-offs, comparison of long-term electrical operating costs of liquid air-cooled transformers must be based on consideration of the operating characteristics of specific transformers.

Noise Levels. Dry transformers have an operating noise level 3 to 6 db greater than liquid-filled units (i.e., 2 to 4 times as noisy). This may be an important consideration if the transformer is to be installed in a building. Additional sound proofing may be required to make indoor dry transformer installations acceptable.

Operating Environment. Open coil air-cooled transformers must be located in fairly clean, dry areas and require protection from weather. Intermittent operation of open coil dry transformers is difficult since the coil insulation can absorb moisture from the air which degrades the electrical properties of the insulation. This is not normally a problem when the transformer is energized because the no-load losses generate enough heat to dry out the insulation. However, care must be taken to dry out open coil transformers before returning them to service if they have been allowed to cool. These transformers are also subject to clogging by the electrostatic attraction of dust to the coils from the cooling air, and periodic maintenance is required to remove the accumulated dust.

Weight and Size. Dry air-cooled transformers generally weigh about the same as liquid-filled units but require up to 20% more floor space. In the case of oil-filled transformers located in buildings, the required vault results in even greater space and weight penalties.

Cast Coil Transformers. Cast coil transformers differ from conventionally wound dry-type transformers in that the high voltage coils or both primary and secondary coils are imbedded in vacuum cast epoxy resin reinforced with fiberglass. This type of construction increases the BIL rating, decreases the noise level, and eliminates the sensitivity to environmental moisture. The cast coil transformers are generally more

(17) Frank, Jerry (Sorgel Electric Corp.), "Watch Out for Energy Losses in Transformers," Electrical Construction and Maintenance, Aug. 1975, pp. 53,4.

compact, lighter, and more shock resistant than either liquid-cooled or open coil dry transformers. The epoxy also provides a heat sink so that the cast coil transformer can withstand temporary overload conditions better than the open coil units.

Satisfactory thermal performance of cast coil transformers is achieved by reducing resistance losses in the coil conductors. This significantly increases manufacturing costs and initial price but decreases electrical operating costs compared to open coil air-cooled transformers.

Although the cast coil transformers are among the most expensive in terms of initial cost, they are being used more and more where reliability, small size, and fire safety are important considerations as in underground coal mine load centers.

2.5.5 Gas-filled Sealed Transformers

A dry transformer can be provided complete protection from environmental effects by sealing it in a pressure tight container and using an inert gas as the coolant. Gas-filled sealed transformers have the same overload limitations as dry air-cooled units, but better control of the insulating media raises the maximum achievable voltages to the same levels possible with liquid filled units.

Several different gases have been used as the coolant in sealed gas-filled transformers. The most commonly used gas in the United States is hexafluoroethane (C_2F_6). Although chlorofluorocarbons are regulated by the EPA, the use of this gas in transformers will probably not be affected by the regulations.* Nitrogen and sulfur hexafluoride have also been used successfully as transformer coolants in certain applications.

Because the inert gas increases in pressure when heated, gas-filled transformers must be enclosed in heavy pressure vessel housings. The pressure vessel increases both the size and weight of the gas-filled trans-

* Phone conversation with Perry Brunner, Office of Toxic Substances, USEPA. Washington, D.C., December 22, 1977.

former compared to open air-cooled units. The price of the sealed gas-filled units is also considerably higher than open air-cooled units. Because of the poorer heat transfer characteristics of the gas compared to liquids, the gas-filled transformers are designed to operate at 150°C coil temperature rise and have insulation systems limited to 220°C. Hot spots in the coils can approach 220°C; accordingly, there is no allowance for even short-term operation at loads higher than rated capacity.

Successful engineering development of a hybrid gas/boiling-liquid transformer could solve many of the heat transfer limitations of the sealed gas-filled design. Such a hybrid transformer could in concept be achieved by using an inert liquid coolant having a low surface tension and an atmospheric boiling point of about 100°C. The amount of liquid used could be one tenth the total void volume with a conventional dielectric gas filling the other 90% of the volume. When the transformer is operating, the liquid would wet the solid insulation by capillary action and would boil off the hot spots providing localized cooling where most required. The vapors would then condense in the cooling coils and run down into the sump. Perfluorocarbon liquids that have the required electrical and physical properties are commercially available. The present high cost of these liquids (on the order of $300 per gallon) would require that the transformer design be optimized to make efficient use of the boiling heat transfer characteristics and to minimize the amount of liquid required.

2.6 Relative Costs of Substitutes for Askarel Transformers

Askarel transformers have been used primarily in those applications where fire safety, reliability and small size have been important factors. Installation of high fire point liquid-filled transformers is allowed by the requirements of the National Electrical Code in the same conditions as PCB-askarel transformers. The only exception is that no outside vent is required for the high fire point liquid units. Since the high fire point liquid units are less expensive than askarel transformers, it is anticipated that the ban on the use of PCBs will have little economic impact provided the high fire point liquid units prove to give equivalent fire safety and performance. It must be realized that the high fire point liquid units have not been proved by long field experience and that questions of relative flammability and the heat of combustion of various liquids have not been thoroughly investigated. Nevertheless, it appears likely that adequate substitutes for new askarel transformers will be developed.

The final choice of a transformer depends on a wide range of technical factors. Given the availability of alternative transformer designs, the final decision must depend on total installed cost, maintenance costs and electrical operating costs. The relative installed costs of alternatives to PCB transformers are summarized in Table 2.6-1.

2.7 Effect of the PCBs Ban on New Transformer Installations

Power Transformers. Very few power transformers have utilized PCBs. The availability of high fire point liquid-filled transformers should provide necessary fire safety at reduced cost. Design alternatives for each installation, including vaults and safer siting of transformers, could allow safe use of oil-filled transformers.

Distribution Transformers. Presently available alternatives to PCB-filled transformers include high fire point liquid-filled transformers and air-cooled, gas-filled and oil-filled transformers in vaults. The high fire point liquid units have not been formally approved, and the evaluation of fire safety is not yet complete. However, this type of transformer is being used and is both less expensive and lighter than equivalent PCB units. Cast coil transformers are also available in sizes to meet most of the previous demand for askarel units, and the higher initial cost is at least partially offset by lower operating costs compared with equivalent liquid-filled units.

Precipitator Transformers. PCBs have apparently been used more to assure long-term reliability with no routine maintenance than to reduce

Table 2.6-1

Cost Comparisons of Oil Filled Versus Other Transformer Designs Intended for Hazardous Locations*
(1000 KVA, 15 KV Transformer)

Type	First Cost	Vault	Catch Basin	Vent	Total Installed Cost
Oil	100%	90-133%			190-233%
PCB (1976)	140%		10%	2%	150%
High fire point hydrocarbon liquid	120%		10%**	***	120-130%
High fire point silicone liquid	140%		10%**	***	150%
Dry open coil air-cooled	150-170%				150-170%
Dry gas-filled	200%				200%
Dry cast coil	150-200%				150-200%

* Adapted from: Westinghouse, "Is There Another Way," Sharon, Pa., p. 18 undated; and Deaken, R.F.J., and Smith, P.D. (Polygon Industries Ltd.), "Epoxy Insulation - A New Generation of Dry-Type Transformers," Paper presented at the 64th Annual Meeting of the Canadian Pulp and Paper Association, Montreal, Quebec, January 31, 1978.

**Catch basin is not required by law or regulation but is required as a condition for insurance coverage by certain industrial insurers.

***Not required by National Electrical Code, but recommended by Westinghouse.

flammability. Manufacturers anticipate no problems from using oil in all new precipitator transformers.

Railroad Transformers. The use of PCBs in railroad locomotives and passenger cars in the United States Northeast Corridor results from a railroad operating rule. Similar equipment using oil-filled transformers has operated successfully in Europe for many years. An experimental locomotive was built in France about 14 years ago to demonstrate the performance of a totally enclosed gas-cooled (sulfur hexafluoride) transformer.[18] The transformer performed well on tests, though it was limited in peak power output because of the overload limitations inherent to dry transformers. That dry gas-filled transformer was not a commercial success because it was more expensive than equivalent oil-filled and PCB-cooled transformers in their electric powered units. During 1973 and 1974, a total of 117 locomotives with silicone-cooled transformers were put in service on the high speed passenger trains serving the Tohoku and New Tokaido Lines.* These silicone-filled transformers have continued to perform adequately.

U.S. railroads changed their operating rules on transformer coolants after the ban on continued use of PCBs was mandated under the Toxic Substances Control Act. AMTRAK tested a locomotive built in Sweden by ASEA, which used a transformer designed to operate with either silicone oil or PCBs. The transformer was initially filled with silicone oil manufactured in Germany and has operated successfully during the AMTRAK tests. Conrail has no restrictions on the entry of the locomotive into the tunnels entering New York City. AMTRAK has indicated that it will probably specify silicone oil as the coolant in all new transformers. The New Jersey D.O.T. is presently taking delivery on 230 new "Jersey Arrow 3" commuter cars which are equipped with silicone-filled transformers.

(18) "Transformateur dans le gaz" ("Gas-Cooled Transformer"), Chemins de Fer, CCXLVI (Issue 3), pp 96-97, 1964.

* Personal Communication: Y. Naka (Hitachi America, Ltd.) to G. Robinson (USEPA), March 17, 1976.

Silicone oil as a transformer coolant is more expensive than PCBs because of poorer heat transfer characteristics and higher cost of silicone. High fire point hydrocarbon liquids have not yet been tested in railroad transformers. If they prove to have adequate fire resistance and performance characteristics, their use would substantially reduce the cost increases caused by the ban on PCBs.

2.8 Maintenance of PCB Transformers

The manufacturing of new PCB transformers essentially ended in 1977. As of 1977, there were about 140,000 units in service. Assuming that the average PCB transformer is 15 years old, it would be expected that the average remaining service life would be 25 years and that the last PCB transformer would not be removed from service for perhaps 60 to 80 years. Calculations of expected remaining service life depend on the accuracy of two assumptions: first, that there will be no regulatory action taken requiring that PCB transformers be removed from service and second, that routine transformer maintenance will be possible and allowable.

2.8.1 Make-Up Liquids for Askarel Transformers

PCB transformers require little maintenance other than occasional checks for leaks and other mechanical damage and routine testing to assure that the liquid has adequate dielectric strength. Significant leakage and degradation of the liquid can lead to both overheating and potential catastrophic failure of the transformer. Leakage can occur at sight glass connections and at gasketed access panels to the taps. Degradation is sometimes attributable to Corona discharge through the liquid. Gradual degradation of the liquid can be due to prolonged exposure to high temperatures and severe electrical fields in the presence of chemically active metal surfaces. Another mechanism for degradation is the absorbtion of moisture from air that may be drawn into the transformer through malfunctioning relief valves or gasket leaks in the vapor area.

Testing the dielectric strength of the PCB liquid in askarel transformers is a routine maintenance practice. Chemical degradation of the liquid and absorbtion of moisture may both cause a decrease in dielectric strength. Should dielectric strength of the PCBs fall below the range of normal values, dielectric properties can be restored by filtering the liquid through Fuller's earth (Diatomaceous earth) to remove moisture and degradation products. Such filtering can be performed using mobile equipment without moving the transformer. Checking the electric properties of the PCBs is normally done at intervals of a year or more. The interval between tests depends on factors including the relative humidity in which the transformer operates, the load factor (determinant of normal operating temperature), and the potential problems that might occur if a major failure was experienced.

PCBs have been routinely used to make up for liquid lost because of leakage, because of removal for sampling, or because it was retained by the filtering equipment while being reprocessed. The ban on the manufacturing and distribution in commerce of PCBs ends the availability of PCBs for transformer make-up. The lack of availability will cause a maintenance problem unless suitable substitutes evolve.

Most transformer askarels have been mixtures of PCBs and trichlorobenzene (TCB). Accordingly, the most obvious make-up liquid would be straight TCB. Increasing the concentration of TCB results in increasing solvent strengths in the dielectric fluid mixture. Since the insulation enamel and other materials of construction were chosen to be compatible with the original dielectric fluid design mixture, there is a maximum safe concentration of TCB. Dilution of the transformer liquid with up to a few percent TCB will probably not cause any problems. However, the transformer manufacturer should be contacted to determine the maximum safe TCB concentration for each particular unit prior to TCB use as a make-up liquid dielectric.

Important factors to consider in converting any askarel transformer to a different liquid include compatibility of the liquid with the materials of transformer construction, maintenance of existing levels of fire safety of the unit, and complete miscibility with the askarel in use. Silicone liquids, for instance, are soluble in askarel up to a concentration of one half of one percent (0.5%). Topping off askarel transformer dielectric fluid with silicone would result either in a layer of silicone floating on top of the askarel or an emulsion of silicone in the askarel. Any such two-phase mixture would be subjected to very high dielectric stresses at the phase boundries. This could lead to corona formation or arcing within the transformer.

The natural and synthetic high fire point hydrocarbon liquids are miscible with PCBs. Tests conducted by RTE Corporation indicated that for various combinations ranging from 100% askarel to 100% RTEmp:*

a. The dielectric strength of the mixture did not fall below that of pure RTEmp.

b. The fire point of the mixture did not fall below that of pure RTEmp.

c. No liquid volume problems occurred since the coefficient of thermal expansion is about the same for askarel and RTEmp.

d. The viscosity of the mixture increased with increasing concentrations of RTEmp, and the transformer operating temperature increased with the viscosity. This effect was negligible at the low concentrations of RTEmp that would normally be encountered in a make-up fluid situation.

e. Mixtures of askarel and RTEmp having a density of about 1.0 could conceivably result in any water present forming a two-phase suspension instead of floating or sinking. This could cause internal arcing in the transformer, although it is unlikely that this much moisture could be present without seriously degrading the dielectric strength of the mixture. RTE Corporation recommended that the concentration of RTEmp used as make-up be limited to less than forty percent by volume to avoid this density range, at least until additional work determines whether a real problem may exist.

* Personal Communication: James B. Caldwell (RTE Corporation) to Robert Westin (Versar), October 14, 1977.

The National Fire Protection Association (NFPA) has not yet considered the status of mixtures of askarel and high fire point transformer liquids in the context of the National Electric Code. The NFPA definition of askarel as being a chlorinated liquid would appear to exclude mixtures of PCBs and hydrocarbons from this class of transformer liquid. However, the only difference between the installation requirements for askarel transformers and high fire point liquid-filled transformers is the requirement of outside venting for askarel transformers to prevent the accumulation of toxic gases inside a building following the occurrence of an arc within the transformer. It seems unlikely that the presence of small amounts of hydrocarbons in the askarel would make any significant change in the toxicity of the gases and, accordingly, the need for outside venting. Since the principal consideration is the effect of the addition of make-up dielectric liquid on the insurability of each installation, the insuring company should be contacted for advice on a case-by-case basis until recognized national guidelines have been developed.

2.8.2 Retrofilling Askarel Transformers

Two conditions that might require complete replacement (retrofilling) of the dielectric liquid in an askarel transformer are:

1. Loss of liquid because of a spill and
2. Such severe degradation of the liquid that it cannot be reclaimed by conventional filter processing.

Replacement with non-PCB liquid would also reduce the liability for damage that would otherwise be caused by a spill of PCBs.

Problems encountered in retrofilling a transformer are the result of differences in lubricity and heat transfer capabilities of the replacement liquid and of the difficulty in removing all of the PCBs from the insulation and windings prior to adding the replacement dielectric fluid. The same considerations apply to the choice of a retrofill liquid as were previously discussed for high fire point transformer liquids and conventional transformer oils.

Extensive experimental work has been done to test the feasibility of retrofilling PCB transformers with substitute liquids. Much of this work has involved the replacement of PCBs with silicone. Three potential problems were investigated in this work:

1. Silicone is less efficient as a heat transfer medium; accordingly, transformers run hotter after being retrofilled with silicone.

2. Silicone has a higher coefficient of thermal expansion, so increased pressures might be expected in a silicone-retro-filled transformer.

3. It is difficult to remove all PCBs from the transformer prior to retrofilling, and residual PCBs remaining in the unit have limited solubility in silicone fluid.

This leads to formation of liquid phase boundries, areas of high electrical stresses, and breakdown of the silicone dielectric fluid. These problems and the basic problems caused by limited miscibility of PCBs and silicones were discussed by Morgan and Osthoff of General Electric.[19] Dow Corning later summarized their experience gained in laboratory and field retrofilling since 1972. According to Dow Corning:[20]

> The pressure increase is about the same in transformers retro-filled with silicone as when filled with askarel because the gas (usually nitrogen) that fills the vapor space is more soluble in silicone than in askarel.
>
> Silicone filled transformers operate 3 to 10°C hotter than do askarel transformers at rated load. However, loss of tensile strength of kraft paper (insulation) on aging in silicone is less rapid than on aging in askarel. Therefore, the higher opera-ting temperatures are not expected to decrease the service life of the transformers.

(19) Morgan, L.A. and R.C. Osthoff, (General Electric Corporation), "Problems Associated with the Retrofilling of Askarel Transformers," IEEE Paper A77-120-9, presented at the IEEE Winter Meeting, 1976.

(20) Page, William C. and Terry Michaud, (Dow Corning Corporation), "Development of Methods to Retrofill Transformers with Silicone Transformer Liquid," IEEE Paper 22-477, presented at the E.I.C. Conference, Chicago, Illinois, September 1977.

> Although all of the askarel could not be removed from the coils when the transformer was initially flushed, and although the concentration of PCB continued to increase in the silicone for several years after the transformer was retrofilled, field experience with a number of retrofilled askarel transformers has not indicated any electrical failure of the silicone fluid or other evidence of premature failure of the transformers.

Operating experience with silicone-retrofilled askarel transformers indicates that the retrofilled transformers operate satisfactorily, although somewhat hotter, than when filled with PCBs. However, it has not been demonstrated that it is feasible to flush the transformers sufficiently to assure that the concentration of residual PCBs in the silicone will be below 500 parts per million (one pound PCB per 2000 pounds silicone). If the concentration of PCBs exceeds 500 ppm, the EPA marking and disposal regulations will require that the transformer be marked as a PCB unit and that the disposal of the contaminated silicones be in accordance with the special disposal requirements for PCBs. Dow Corning has reported that, based on experience with ten transformers, proper solvent flushing of small askarel transformers (167 to 1000 KVA) has resulted in an initial level of PCB contamination in the silicone of between 0.13 and 0.77 percent.(21) The concentration of PCBs in the silicone slowly increased after the transformers were placed in service. The increased level of PCBs was caused by residual askarel slowly leaching out of the paper insulation and coils into the silicone. PCBs concentration reached a level of from one to four percent after the transformers were in service for 2 to 3 years. This concentration is well below the solubility limit of PCB in silicone (reported by GE to be 10% at 25°C and 12% at 100°C - Morgan and Osthoff, 1976). At concentrations of 1 to 4%, no phase discontinuities will occur in the silicone coolant liquid. However, the leaching process is accompanied by the presence of PCB and silicone liquid phases in the insulation and kraft paper. The practical limit for reduction of PCB concentration in field retrofilling has

(21) Page, William C. (Dow Corning Corporation), Statement on retrofilling made at the EPA public meeting on the implementation of the proposed PCB ban, Chicago, Ill., July 19, 1977.

been estimated to be in the range of 0.3 to 1% PCB in the silicone when the transformer is initially returned to service. The cost of such a retrofill program to replace askarel with silicone was estimated to be about $30.00 per gallon.[22] Detailed retrofill instructions are available from Dow Corning.[23]

The feasibility of removing PCBs from a transformer by flushing with solvent depends on both the procedure used and the design of the transformer. The Federal Railroad Administration has sponsored two research projects which have retrofilled and tested transformers from commuter cars. The transformers were 418 KVA units containing 168 gallons of askarel. The projects were performed by General Electric Company and Westinghouse.

The work performed by General Electric Company indicated that hot draining of the transformer removed 85% of the askarel and that circulating hot silicone fluid through the transformer for 288 hours reduced the residual askarel to 107 pounds. PCBs and trichlorobenzene were removed at the same rate, and the rate of leaching of residual askarel into the silicone was found to be diffusion limited. Operating tests showed that the transformers ran 9.7°C hotter with silicone than when filled with askarel. GE suggested that the temperature increase would have been 15°C had the cooling fins not been steam cleaned during the flushing procedure. GE did not report any conclusions as to the long-term performance reliability of the retrofilled transformer, but they did suggest that the two-phase liquid existing in the coils might eventually cause problems.[24]

Westinghouse retrofilled a similar transformer. Initial flushing was with mineral spirits, followed by circulation of silicone. Performance

(22) Transformer Consultants (Akron, Ohio), "Silicone Retrofill of Askarel Transformers," The Consultor, January 1977.

(23) Dow Corning Corporation (Midland, Mich.), Retrofilling with Dow Corning 561(R) Silicone Transformer Liquid, October 19, 1976.

(24) Foss, Stephen D., John B. Higgins, Donald L. Johnston, James M. McQuade, (General Electric Company), Retrofilling of Railroad Transformers, Report No. DOT-TSC-1293, July, 1978.

tests indicated no increase in the winding to fluid temperature differential and a 2.7^{o}C increase in the liquid temperature following retrofilling with silicone. Continued operation of the retrofilled transformer resulted in an increase in the concentration of PCBs in the silicone to 3.47% after two weeks of operation and 4.37% after four months of operation. The final report concluded that there was no reduction in operating performance of the retrofilled transformer and that long-term performance should be satisfactory, although it could not be determined what the equilibrium concentration of PCBs would be in the silicone.[25]

There has been little information published on the performance of askarel transformers retrofilled with other liquids. Both conventional transformer oil and the natural and synthetic high fire point transformer liquids are completely miscible with askarel. Because of this miscibility there should be no problems associated with liquid phase boundries. If an askarel transformer were retrofilled with transformer oil, it would need the fire protection normally required for oil-filled transformers, such as a vault and/or sprinkler. The unit would also be considered a PCB unit for purposes of marking and disposal as long as the concentration of residual PCBs exceeded 500 ppm. A transformer retrofilled with a hydrocarbon liquid would be subject to the same marking and disposal restrictions, but it would need venting and vault protection as either a high fire point transformer or an askarel unit depending on the advice obtained from the insurer. In either case, the retrofilled unit would be expected to operate satisfactorily. Guidelines for flushing and retrofilling askarel transformers with hydrocarbon liquid are available from RTE Corporation.[26]

(25) Walsh, E.J., D.E. Voytik, H.A. Pearce, (Westinghouse Electric Corp.) Evaluation of Silicone Fluid for Replacement of PCB Coolants in Railway Industry, Final Report, Report No. DOT-TSC-1294, December 1977.

(26) Olmstead, John (RTE Corporation), Comments and Recommendations on Retrofilling of Transformers, Waukesha, Wisconsin: RTE Corporation, October 31, 1977.

2.8.3 Removal of Residual PCBs from Non-Askarel Transformer Liquids

Retrofilling an askarel transformer with a non-PCB liquid reduces the potential damage that might occur if the transformer were to fail or be ruptured. Significant cost savings would only be achieved if residual PCBs could be reduced below the minimum concentration that requires labeling and disposal as PCB-contaminated equipment. This degree of decontamination cannot be achieved in a short period of time by flushing the transformer with solvent since complete removal of PCBs from the insulation and coils is limited by the rate of diffusion of PCBs into the bulk liquid. The concentration of PCBs in transformers retrofilled with silicone fluid has been observed to increase for several years following the return of the transformer to service. If the contaminated dielectric liquid were replaced every year or two with clean transformer liquid, residual PCBs would be eventually eliminated from the transformer. Demonstration of feasible dielectric fluid decontamination processes allowing immediate use of the fluid would make this alternative highly attractive.

Recent evaluations have demonstrated that PCBs and trichlorobenzene are selectively adsorbed from silicone liquid by activated carbon. Dow Corning has demonstrated this process on a laboratory basis using contaminated silicone from a retrofilled transformer that had been in service for ten months.[27] When the transformer was retrofilled, the concentration of residual PCB in the silicone was 0.7%. This concentration increased to 2.53% after ten months. The silicone also contained 5.47% trichlorobenzene at this time. Filtering the 180 gallons of liquid through 120 pounds of activated carbon for eight hours reduced the concentrations to 0.43% PCB and 1.80% TCB. Five weeks later these concentrations had increased to 0.615% and 2.09%, respectively. The contaminated liquid was then filtered for 5 hours through 120 pounds of fresh activated carbon, and finally through 60 pounds of a third batch of activated carbon filters for one hour. The residual concentrations after

(27) Dow Corning Corporation, Removal of PCB from Dow Corning 561(R) Transformer Liquid by Charcoal Filtration, undated.

this treatment were 472 ppm PCB and 0.296% TCB. This left a total of 0.68 pounds of PCB in the liquid and an unknown amount in the coils and insulation. The filtering was done by pumping the silicone liquid at a rate of 5 to 8 gallons per minute through Brute(R) Cartridge Filters manufactured by DC Filter and Chemical, Inc. Each of the filters contained 20 pounds of Nuchar WV-XG(R) granular activated carbon manufactured by Westvaco.

For those transformers equipped with a pump, it appears possible to install a carbon cartridge filter of the type used by Dow Corning adjacent to the pump. The filter would continually scavenge residual PCBs from the silicone after most of the PCBs had already been replaced by retrofilling of the transformer. This procedure might prevent the level of PCBs in the liquid from increasing to concentrations above 500 ppm. The transformer then would no longer have to be classified as a PCB unit. In addition to the reduction in spill risks, successful decontamination of an askarel transformer would mean that when the transformer is finally scrapped, special PCB disposal procedures would not be required. The decontaminated transformer could then be sold for scrap instead of being drained, flushed, transported to an approved chemical waste landfill, and buried. Disposal savings could be considerable, as present charges for disposal in chemical waste landfills are in excess of one dollar per cubic foot.

The decontamination of silicone transformer liquids is still in the experimental testing stage. Westinghouse Electric Corp. has reportedly applied for a patent on the process of using activated carbon to remove PCBs from silicone. No results have been made public on techniques to remove PCBs from hydrocarbon transformer liquids, although RTE Corporation is reportedly doing research in this area at the present time.

2.9 The Economic Impacts of Changes in the Expected Service Life of Presently Used Askarel Transformers

The EPA ban regulations will apparently allow the continued use of PCB transformers but will ban maintenance that would require removal of the transformer coils from the tank. Continued use of the transformer would require that the user assume any risks associated with a PCBs spill.

The resulting economic impact on transformer users will depend on both the availability and suitability of make-up liquid and on the availability and price of replacement transformers with size and fire safety characteristics comparable to askarel units in use. Assuming that trichlorobenzene or high fire point transformer liquids will prove to be satisfactory as make-up liquids, and assuming that high fire point transformers will be available for use as specified by the 1978 National Electrical Code, the only economic impacts associated with the reduction in transformer service life will be due to the ban on a major rebuilding of failed transformers.

Most transformer maintenance involves cleaning of tap changers, replacement of gaskets and busings, filtering of dielectric liquid, repair of minor leaks, and repainting. None of these repairs require that the core be removed from the transformer casing. Electrical failure can be caused by deterioration of the insulation or exposure to voltage surges due to lightning or other causes. The resulting arcing from phase to phase, phase to ground, or phase to core damages the transformer winding. Repair of this damage requires that the transformer be completely disassembled, the damaged windings replaced, and the transformer then essentially rebuilt. These major repairs return the transformer to "like-new" condition but would not be possible if the removal of the transformer core were banned by the regulations.

Major rebuilding of an askarel transformer costs from fifty to seventy-five percent of the price of a replacement transformer. The failure of an askarel transformer often results in complete power loss to the installation serviced by the unit until the transformer is repaired or replaced. Because there are many types of askarel transformers in service and few spares available, it is rare that an equivalent transformer can be substituted for a failed transformer. Electrical service to the installation will remain disrupted until the transformer is repaired or replaced.

The transformer repair industry is geared to providing emergency service, with major repairs to most failed transformers accomplished in seven to ten days. In contrast, delivery of new transformers usually requires 12 to 18 weeks from the date of order. This time is required primarily to specially fabricate the core and casing.

Although many large factories and buildings depend on three or more identical transformers for power so that the failure of one transformer will not disrupt the operations of the entire facility, many small operations (less than 500 employees) are serviced by a single transformer. Disruption of service for the three to four months required to purchase a new transformer could have serious economic consequences.

Because of the expected demand for replacement transformers on a priority basis, it is expected that the transformer manufacturers will increase their inventories of new or loaner units to meet the needs of their customers. Although incidents of production loss (that could be reduced by the availability of rebuilding services) will probably continue, the likely response of industry will be to provide the equipment to minimize these losses. The effect of the ban on PCBs in transformers will therefore result in changes in transformer technology and changes in the structure and responsiveness of the transformer manufacturing industry.

3.0 ELECTROMAGNETS

Polychlorinated biphenyls have been used as an electrical insulating liquid in some electromagnets used to scavenge tramp iron from coal carried on conveyor belts. These separator magnets are similar in construction to a transformer, having a single coil on a magnetic core immersed in liquid and contained in a leak proof case. The heat generation of the unit and the required properties for the insulating liquid are similar for both transformers and separator electromagnets.

PCB filled magnets were supplied on special order by three different manufacturers:

Sterns Magnetics, Cudahy, Wisc.
Eriez Magnetics, Erie, Pa.
Dings Co., Milwaukee, Wisc.

The separator electromagnets manufactured by these companies are suspended over the conveyor belts where they attract any tramp iron from the coal before it can be carried into the crusher and possibly damage the equipment. Each of the magnets of the type used over coal conveyors contains about 135 gallons of liquid. The standard insulating liquid used by all of these manufacturers was transformer oil, but special liquids, including PCBs, were used when required by the customer's specifications. About 200 PCB magnets were manufactured in the U.S. before manufacturers voluntarily stopped manufacturing them. Sternes Magnetics stopped using PCBs in 1972, Eriez Magnetics stopped in 1971, and Dings Co. stopped in 1976.

The PCB-filled magnets were furnished only for coal conveyors in the U.S. and for a few grain conveyors in Canada.

The failure rate of separator electromagnets has been estimated to be less than one percent per year. Failure has usually been caused by mechanical damage to the case rather than to electrical arcing and failure. The ban on the use of PCBs is not expected to have a significant impact on the operation of the magnet manufacturers or the continued maintenance and use of existing magnets.

All three electromagnet manufacturers have successfully used transformer grade silicone fluid as an insulating liquid in separator electromagnets of standard design. It is expected that other high fire point transformer liquids will be developed and will be usable in separator electromagnets, In addition, Eriez offers a proprietary air-cooled electromagnet which has Underwriters Laboratory approval for use in dusty and dirty environments.

4.0 ELECTRIC MOTORS

Reliance Electric Co. built the only electric motors known to use PCBs as a coolant. Those motors were installed on certain coal mining machinery manufactured by Joy Manufacturing Co.

4.1 The Use of Liquid-Cooled Motors in Mining Machinery

The designing of electric motors for use on mining machinery presents a number of geometric and operational problems. Mining machines for underground use in low coal seams are designed to an overall height limitation as low as 22 inches. The width of continuous miners must be less than the width of the cutting heads, and other equipment must be able to operate in narrow, low seams. Accordingly, the space available for mounting electric motors is very limited. In addition, the motors must be able to operate in wet, dirty environments and perform under an intermittent duty cycle.

A basic limitation to the size of electric motors in imposed by the generation of heat and the need to remove this heat from the windings and rotor. This heat is generated in much the same manner as heat is generated in transformers. The motors used in mining equipment are totally enclosed to protect the them from dust and moisture in the mine and to isolate flammable dust and methane gas from flame or sparks emitting from the motor if methane is ignited inside the motor. The motor casing is either air cooled or water jacketed to remove heat. Heat transfer limitations are governed by the transfer of heat from the windings and rotor to the fins or water jacket of the motor. Most motors are designed so that heat convection by the air between the rotor and stator windings will be sufficient to transfer heat to the cooling surfaces. As in the case with transformers, greater efficiency in heat transfer can be obtained by immersion of the heat generating components in a liquid. Because they have more efficient heat transfer characteristics, liquid-cooled motors can be built smaller than air-cooled motors of equivalent horsepower.

Motors cooled with petroleum based hydraulic fluid were first used in mining machinery in the early 1960s. However, the potential flammability of this liquid made it unsuitable and led to the decision to use a less flammable liquid as the coolant.

A number of mining machines built in the late 1960s by Lee Norse used silicone-cooled motors manufactured by Westinghouse. Because silicone is expensive, its use was not a satisfactory solution and only a few of these machines are presently in service.

According to Mr. Warner of Joy Manufacturing Company,[28] PCB-cooled motors manufactured by Reliance Electric were used in three types of mining machinery built by Joy:

1. Fifteen type CU43 continuous miners were manufactured in the period 1963 through 1967. Each of these machines used three PCB-cooled motors. Two motors were installed at the front of the machines adjacent to the cutting heads; they supplied power to the cutters. The third motor was installed on the frame of the machine to provide power to the hydraulic system that adjusts the cutter heads. These motors were 13 ½ inches in diameter, 26 inches long, and were rated at 115 horsepower. Each motor contained about three gallons of PCBs. The motors were water jacketed and were cooled by the water that was then sprayed on the face of the coal seam to reduce dust. A survey by Versar in late 1977 identified only one mine that was still using CU43 miners. This mine had three operational machines and was using two machines full time in production and one as a spare. Most of the motors on these machines had been converted to silicone oil coolant. In addition, the mine bought a number

(28) Warner, Edmund M., (Joy Manufacturing Company), Presentation to Environmental Protection Agency sponsored public meeting on PCBs, Chicago, Ill., July 19, 1977.

of other used CU43 miners which it now uses as a source of repair parts. This is a rather large mine, and the CU43 miners account for probably less than ten percent of the total production of coal.

2. Fifty-seven type 9CM continuous miners were sold by Joy Manufacturing for use in the United States from 1967 to 1970. Three PCB-cooled motors are used in each machine, two built into the cutting heads to provide power to the cutters and one on the frame to power the hydraulic system. The motors are jacketed and are cooled by the water that is sprayed on the face of the coal. A survey conducted by Versar in November 1977 determined the status of these 9CM miners as follows:

Idle/junked	23
Full time production	11
Operational spares	2
Non-production mine use	2
Educational/training use	1
Unknown	18

3. Five hundred fourteen type 14BU10 loaders were sold to a total of 88 different customers from 1965 to 1973. These loaders are used in conventional mining where the coal is broken by blasting and then loaded onto shuttle cars which carry it to a conveyor. The loaders are used to scoop up the coal and dump it onto the shuttle cars. Each of the 14BU10 loaders has two PCB-cooled motors which are used to provide traction power to the machines. Each motor is 17 ½ inches in diameter, is 20 1/8 inches long, has fins cast into the motor casing to provide heat transfer surfaces to the surrounding air, and is rated at 25 horsepower. Each motor contains about three gallons of PCB which significantly reduces the operat-

ing temperature of the motor, thereby increasing significantly its expected service life. As of July 1977, Joy had converted 353 of these motors to dry (non-PCB) operation. Many of the 14BU10 loaders were originally purchased by small mines, and it is not known how many of these machines remain in service.

4.2 Substitutes for PCBs in Electric Motors

The only motors using liquid coolant are those that have been designed for applications where space is extremely limited. The use of a liquid coolant introduces two new problems into the design of a motor: first, the bearings must be able to operate in the liquid, and second, the shaft seals must be able to prevent leakage of the liquid when it is under pressure caused by thermal expansion of the liquid when the motor generates heat. These problems have never been completely resolved, and there are no new machines presently being built that utilize liquid-cooled motors.

The need for substitutes for PCBs in electric motors is based on the need for maintenance of the existing Joy continuous miners and loaders using PCB-cooled motors. Beginning in 1974, Joy provided a conversion kit to change the 14BU10 loader motors to conventional dry construction. Joy estimates that the normal failure rate of the PCB-filled motors would result in all of the motors being rebuilt as dry type motors by the end of 1981 if the EPA forbids the continued use of PCBs in maintaining this equipment.

The PCB-cooled motors in the continuous miners cannot be converted to dry operation. A number of these motors have been rebuilt using transformer grade silicone oil as a coolant and have performed satisfactorily. They were converted because previously, silicone oil-filled motors had been supplied by Lee Norse on certain mining machines that had been approved by the Mining Enforcement and Safety Administration (MESA) for use in underground mines.

Review of the use of silicone liquids in coal mines has identified a potential problem with the methane detectors that are used in these mines and are mounted on the mining machines. The concentration of methane in the air is measured by determining the amount of heat generated on a platinum catalyst by catalytic oxidation of hydrocarbons in the air. It has been found that silicone vapors will poison the catalyst, thereby gradually reducing the sensitivity of the detector. It is standard practice in the coal mines in Great Britain to protect the methane detectors from silicone poisoning by using an activated carbon cloth to selectively adsorb any silicones from the air before the air is passed over the catalyst. However, in Great Britain the methane detectors are carried by safety inspectors and are calibrated every shift. Periodic maintenance of the detector and replacement of the carbon cloth is therefore fairly easy. In the U.S., the detectors are mounted on the machines and operate in a wetter environment than would be experienced by units that are carried by inspectors. This moisture may tend to reduce the effectiveness of the carbon. It would also be difficult to ensure proper maintenance of machine-mounted detectors.

The U.S. Mine Enforcement and Safety Administration is reportedly planning to inform all coal mine operators of the potential problems that might be caused by the use of silicones as motor coolants for mining equipment. Both the U.S. Bureau of Mines and the major manufacturer of methane detectors are investigating the feasibility of protecting the detectors should a spill of silicone occur. Therefore, the acceptability of silicones as a replacement fluid for PCBs in the motors on the Joy continuous miners must be considered problematical in spite of recent satisfactory experience.

Reliance Electric has evaluated a number of other liquids as potential substitutes for PCBs in these motors. The criteria for acceptable flammability which they have established requires that no flames or generation of flammable gases occur following a major electrical arc through the liquid. None of the high fire point hydrocarbon transformer liquids (or the silicones) can pass this test. Trichlorobenzene was determined to have adequate fire resistance, but the smell of the vapors was felt to be too irritating to allow the use of this chemical in motors used in underground mines. Therefore, Reliance and Joy have reported that a satisfactory substitute for PCBs does not exist for the motor application.

Fortunately, the lack of an adequate substitute will not have a major economic impact. A ban on the continued use of PCBs would result in the early retirement of twelve continuous miners from coal production. Most of these machines are already near the end of their economic life and would not have been used for more than an additional two or three years. An informal survey of manufacturers of mining machines in late 1977 indicated that the lead time for delivery of new continuous miners was two to six months, depending on the manufacturer and the model ordered. The manufacturers do not feel that an immediate demand for 25 or 30 machines would have a significant impact on this delivery schedule. In addition, used machines are available which could replace the Joy continuous miners that use PCB-cooled motors.

5.0 CAPACITORS

PCBs have been used as a dielectric liquid in alternating current capacitors since 1930. The PCB units are about one half the size and are much more reliable than the previously used mineral oil impregnated capacitors. PCBs also have the major advantage of being non-flammable. Alternative dielectric liquids and capacitor designs that do not use a liquid dielectric have been developed, but none of these combine the features of long life, high dielectric constant, and low price that have made PCBs so attractive.

The Toxic Substances Control Act banned the use of PCBs in manufacturing capacitors effective January 1, 1979. Since no equivalent liquid dielectrics are available, capacitor manufacturers have been forced to redesign their products and introduce capacitors using new liquids after limited service testing.

The following sections discuss the use of PCBs in capacitors and the substitute materials which are being used and considered for use.

5.1 Principles of Capacitor Operation

Electrical capacitors are devices that store energy in the form of an electric field between two parallel conducting plates when a voltage differential is applied across the plates. This stored energy reappears as electrical current when the voltage difference is decreased. The capacitor therefore performs an electrical function equivalent to that of a spring in a mechanical system.

If an alternating voltage is applied across a capacitor, the electric field between the plates opposes the applied voltage. This apparent resistance varies throughout each cycle and will control the flow of current through the capacitor. At the start of the cycle when the voltage across the capacitor is zero, there is no opposing electric field and therefore no resistance to the flow of current. When the voltage is at a maximum, the opposing field is also at a maximum, and the current is therefore at a minimum. As the voltage decreases to zero, the energy stored in the electric field reappears as current in a direction opposing the applied voltage. Thus, the current flowing through a capacitor leads, or precedes in time, the voltage across the capacitor.

The amount of energy stored in the electric field in a charged capacitor depends on the intensity and size of the electric field. The intensity of the field increases with increasing voltage and decreasing distance between the plates, and the size of the field increases with increasing plate area. The amount of energy that can be stored in a capacitor of a given size and configuration is measured in units of capacitance.

If a dielectric material is placed in an electric field, surface charges appear on the material in such a way that the surface charges oppose the applied voltage. The dielectric material absorbs energy from the electric field in developing this resisting field, so the total amount of energy stored in a capacitor (i.e., the capacitance) is increased when a dielectric material is present between the plates. The ability of the material to increase the capacitance is referred to as its dielectric constant. The dielectric constant is defined as the ratio of the capacitance of a device when the material fills the space between the plates to the capacitance when there is a vacuum between the plates.

An ideal dielectric material would give up all of the stored energy in the form of current when the imposed electric field was removed. Real materials always absorb a certain amount of the energy which then appears as heat. As a result of this absorbtion of energy, the charging current in a real capacitor will lead the voltage by slightly less than the 90 degrees that would be expected for a perfect capacitor. The angle by which the current differs from 90 degrees is known as the dielectric loss angle and is a measure of the efficiency of the dielectric material in storing energy. This relationship is often reported as the loss tangent, which is the tangent of the loss angle. The total portion of energy lost through dielectric heating of the material is the dielectric power factor, which for most materials is approximately equal to the product of the dielectric constant and the loss tangent.

Energy can also be generated in a capacitor via the conductance of electricity by the dielectric material which results in resistance heating. The resistivity of the material is a measure of the degree to which the conduction of current is resisted by the material.

The distribution of voltage between the plates of a capacitor depends on the distance between the plates, the average imposed voltage, and the geometry of the plates. In general, the voltage stress (rate of change of voltage with distance) is proportional to the diameter of the charged surface, so high voltage stresses are experienced at plate edges and at any rough areas or projections from the plates.

Sufficiently high levels of applied voltage stress can cause electrons to be separated from the molecules of the material and to thereby become available to conduct current. The voltage stress at which this ionization will be initiated for a particular material is known as the corona inception voltage. If this voltage stress is exceeded, the dielectric material becomes a conductor, resulting in greatly increased resistance heating. Once corona discharges start in a material, they continue until the voltage is decreased to a level below that at which the discharge started. Capacitors operating on alternating current would be expected to have small areas of corona discharge every cycle at localized edges and rough areas of the conducting plates. To minimize the time that this condition continues when the voltage decreases, it is important that the corona extinction voltage be as high as possible.

If several dielectric materials are present between the conducting plates, the voltage stress is distributed across the materials in a ratio inversely proportional to the dielectric constants of the materials. For instance, if the dielectric material is porous paper having a dielectric constant of 6 which contains air having a dielectric constant of 1, the voltage stress across the air will be 6/7 of the total applied voltage, and the stress across the paper will be 1/7 of the total.

Air has a fairly low corona inception voltage and a dielectric constant of about 1. Therefore, air bubbles in the dielectric material in a capacitor will be subjected to high voltage stress levels which will result in corona formation at relatively low levels of applied voltage. For this reason, most A.C. capacitors are impregnated with a dielectric liquid that displaces the air from the porosity of the solid dielectric and fills the gaps between the plates (usually metal foil) and the solid dielectric material that structurally separates the plates. This liquid also absorbs gases formed by corona discharges and flows into any vapor pockets which may be formed by corona or minor arcing. Therefore, liquid impregnated capacitors are to some extent self healing, a feature that explains their reliability.

The charges in a capacitor are carried by the surface of the plates. There is no requirement that these plates be thick to ensure mechanical strength or current carrying capability provided the solid dielectric material(1) supports the plates and maintains close, constant spacing between the plates and (2) prevents short circuits. The normal construction of ac capacitors uses alternating layers of aluminum foil and special kraft paper tightly wound on a mandrel. This core is then vacuum impregnated with a dielectric liquid and sealed into a metal can. Where the voltage stress is expected to be high, as in high voltage power factor capacitors, plastic film or bi-layer plastic film/kraft paper solid dielectric materials may be used.

The production of satisfactory A.C. capacitors depends on careful control of the design and of the material properties. Many different combinations of plate spacing and solid and liquid material properties are available. Optimum capacitor design depends on careful engineering backed by the data from extensive long-term performance tests. Since the service life of the capacitors will depend on the slow degradation of the dielectric materials, long-term testing is necessary to determine the most appropriate material combinations, voltage stress, temperature, and manufacturing processes.

5.2 Uses of Electrical Capacitors in Alternating Current Circuits

If a voltage is applied across a device that generates a magnetic field, such as a motor winding, energy is used to create the magnetic field. This energy reappears as current when the voltage decreases and the magnetic field collapses. In the case of a winding energized by alternating current, the alternating magnetic field opposes the applied voltage, so the voltage drop across the device is proportional to the rate of change of current. When the magnetic field is at a maximum, the opposing voltage is also at a maximum, and the voltage drop across the device is at a maximum. Therefore, the current flow is zero. As the voltage decreases, the magnetic field collapses resulting in a current in the same direction as the voltage drop, but lagging the voltage drop in time. Therefore, such a device results in a shift in the time relationship between voltage and current opposite to that caused by a capacitor. This type of phase shift is caused by electric currents induced by changing magnetic fields, and such equipment is called inductive.

In an A.C. circuit that has a capacitor and an inductive device in series, the current generated by a collapsing magnetic field occurs at the same time that the electric field is being formed in the capacitor. When the capacitor is discharging current, the magnetic field is increasing and is taking energy from the circuit. Because of the difference in the direction of phase shifts, energy is transferred back and forth between the magnetic field in the magnetic device and the electric field in the capacitor. If the phase shift caused by an inductive device is not compensated for by a capacitor, the electric energy generated by the collapsing magnetic fields will be transmitted back toward the generator and will be dissipated as heat in the transmission lines.

A.C. capacitors are widely used to compensate for the phase shifts caused by magnetic devices. PCBs have been used as dielectric liquids in these capacitors since the 1930's. A.C. capacitors containing PCBs usually have a very low failure rates; the rate depends on the particular design and use, but it is usually no more than one or two percent per year. Because of this low failure rate, most of the PCB capacitors manufactured are still in service. The present location of these capacitors depends on their particular design and use.

5.2.1 High Voltage Power Factor Capacitors

The normal loads imposed on utility distribution systems are a combination of resistive (resistance heating, lighting) and partially corrected inductive loads. As a result, the current lags voltage. This condition results in excessive transmission losses and lowered efficiency unless the phase relationship is corrected by installation of extra capacitors in the system near the inductive loads.

The power lost in transmission because of the resistance in lines is proportional to the square of the current. However, the power delivered to the user is equal to the voltage times the current. Transformers are therefore used (1) to raise the generated power to high voltages (and low amperages) for long distance distribution on high towers, and (2) to lower the voltage to intermediate levels at substations for local distribution, and (3) to further lower the voltage to line voltages (110 volts to 660 volts) near the site of its use.

Large high voltage power factor capacitors are installed by the utilities on the intermediate voltage transmission lines to compensate for the phase shifts caused by the use of the electricity. These capacitors operate at from 4800 to 13800 volts (occasionally at 2400 volts). There is some heat generated in an operating capacitor, which must be radiated or conducted from the surface of the unit. To prevent overheating, commercial power factor capacitors are limited to that size where heat loss from the capacitor case will be adequate to prevent overheating. The usual size of such capacitors may be 4" x 8" x 2' high, weighing 100 to 150 pounds including 3 gallons (30 lb) of PCBs. These capacitors are usually installed at substations in frames which hold a large number of identical units. The capacitors are also often mounted at the top of distribution poles.

There are presently four companies in the United States that manufacture large high voltage power factor capacitors:

Westinghouse Electric Corp.
General Electric Co.
McGraw Edison Co.
Sangamo Electric Co.

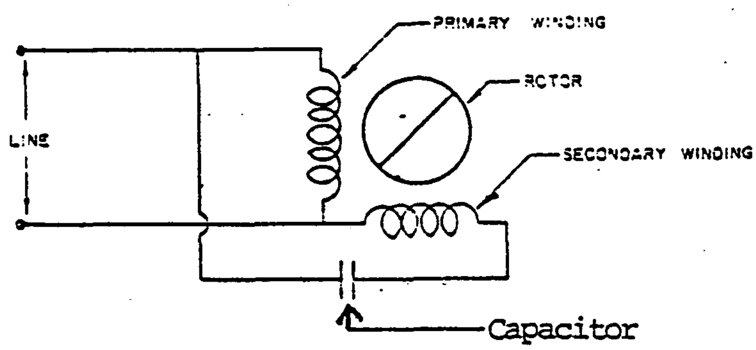
Approximately ten million pounds of PCBs per year were used in the manufacture of these large capacitors from 1972 to 1975. Total production was probably on the order of 300,000 to 400,000 units per year, and there are probably four to six million of these large high voltage power factor capacitors currently in use. Most of these capacitors are owned by utilities and are located in secure locations such as in substations and on power poles.

The market for these large capacitors has been very competitive. Although capacitors made by all of the manufacturers contained PCBs prior to 1977, the capacitor designs were constantly modified in a continuing effort to decrease manufacturing costs.

5.2.2 Industrial Capacitors

Capacitors made for various A.C. industrial applications have in the past all been based on the use of aluminum foil, kraft paper, and PCB liquid dielectric. This combination of materials has provided good life and excellent fire safety at low cost. Most of these capacitors are rated at 330V, 370V, or 440 volts. The conditions under which these capacitors operate in various applications will affect the usability of proposed substitutes for PCBs. Some of the major types of industrial capacitors are as follows:

Motor Run Capacitors: Capacitors are used in single phase A.C. motors both to provide starting torque and to increase the electrical efficiency of the motors by correcting the power factor of the equipment. In a capacitor run motor, the windings are connected as shown below:



The effect of the capacitor in series with the secondary winding is to shift the phase relationship of the voltage and current through this winding so that the magnetic fields in the primary and secondary windings are out of phase by approximately 90 degrees. As a result, the stator "sees" an essentially rotating magnetic field that causes a high starting torque. Because of the inductive effect of the starting winding, the voltage in this leg of the circuit is substantially above the line voltage. Most motors are designed so that the capacitor operates at an effective applied voltage of 370 volts A.C.

The motor run capacitor also provides significant power factor correction, thereby increasing the efficiency of the motor. Small A.C. motors, such as those used in refrigerators and small fans, do not require a high starting torque and do not presently have capacitors. However, regulations promulgated by the Department of Energy which establish goals of improved efficiency of appliances are expected to greatly increase the demand for small motor run capacitors over the next few years.

Ballast Capacitors: Most fluorescent lights and high intensity discharge (mercury and sodium vapor) lights operate on 110 volt circuits. However, a voltage of at least 300 volts across the bulbs is required to produce a sufficient flow of current to operate them. This high voltage is produced by a ballast transformer (in the case of fluorescent lights, an autotransformer). Control of the current is important, because the bulbs have a high resistance when first started, and this resistance drops as the bulbs are heated.

Most small fluorescent lights do not have ballast capacitors. These include the 15 watt and 20 watt single tube household fixtures. The ballasts of dual - 40 watt fluorescent fixtures and larger fluorescent and high intensity discharge lamps have ballast capacitors in series with the transformer and bulb to limit the current flow and correct the power factor of the fixture. For instance, the small fixtures have a power factor of about 0.7; the larger units with ballast capacitors operate at a power factor of 0.9 or above.

The standard ballast used in fluorescent light fixtures with dual 40 watt or single 80 watt bulbs consists of a small 4 uf capacitor and an autotransformer which are both encased in a steel can and potted in a mixture of asphalt and sand. The capacitor is of the usual foil-paper-liquid dielectric construction which is sealed in a metal can before being assembled into the ballast.

Ballasts for high intensity lighting fixutres also consist of a transformer and one or more capacitors which are usually mounted as separate components rather than being permanently sealed into a ballast container. Standard highway HID fixtures often use two capacitors, each being about 2" x 4" x 6". In explosion-proof HID fixtures, the light, transformer, and capacitors are hermetically sealed into an explosion proof housing. The temperature of the capacitors may exceed 90° C in these fixtures because of the poor heat transfer characteristics of the fixture.

Appliance capacitors: Small capacitors are widely used in microwave ovens as part of the high frequency generating circuits and in some television sets in the circuit that compensates for fluctuating line voltage.

Surge capacitors: The circuit breakers (switches) used on large inductive machines must be protected from excessive arcing across the terminals. If an inductive device such as a transformer or motor is disconnected while the coils are energized, the magnetic field will collapse and the energy will appear as an electric field in the lines between the device and the circuit breaker. These lines will act as a capacitor, the energy being proportional to the capacitance and the square of the voltage. Since the capacitance of the connecting lines is quite small, several thousand volts may appear as a transient which will cause arcing across the terminals. The addition of a surge capacitor on the machine side of the circuit breaker increases the capacitance, thereby reducing the maximum transient voltage and protecting the circuit breaker.

Industrial capacitors: A.C. capacitors are also used in surge protection for silicon controlled rectifiers; in the power supplies of arc welders and induction furnaces; and in business machines, electronic controls, and similar electronic equipment.

5.3 Desired Properties for Capacitor Dielectric Liquids

The primary dielectric in the A.C. industrial capacitors is the solid dielectric which maintains a constant distance between the aluminum foil plates. The purpose of the liquid is to displace air, thereby raising the corona inception voltage of the device and the maximum operating voltage of the capacitor. The liquid also absorbs any gases that are formed and flows to fill any bubbles that may result from minor arcing; this makes the capacitor self-healing. It is important that the chemical, physical, and electrical properties of the liquid be compatible with those of the other materials and with the way the capacitor will be manufactured and used. Important liquid properties include:

Electrical properties:

Dielectric Constant: Should be close to that of the solid dielectric (6.15 for paper; 2.2 for polypropylene).

Loss Tangent (dissipation factor): As low as possible to minimize dielectric heating of the capacitor which wastes energy and shortens the life of the device.

Resistivity: As high as possible initially, and remaining high after extended use to minimize resistance heating.

Dielectric Strength: As high as possible to prevent arcing.

Corona Inception Voltage: As high as possible, to allow the capacitor to be built with minimum plate spacing and high electric field strengths. High corona inception voltage will also minimize corona at the edges of the foil and at other rough or sharp areas.

Corona Extinction Voltage: As close to the corona inception voltage as possible to minimize the length of time that corona discharge will occur during each voltage cycle.

Physical Properties:

Viscosity: Capacitors are impregnated with liquid by placing them in a vacuum chamber, evacuating the air, and flooding the chamber with liquid that soaks into the pores of the solid dielectric by capillary attraction. It is important that the viscosity of the liquid be sufficiently low to allow it to flow into the capacitor at a temperature where the vapor pressure of the liquid is also low. The liquid must also wet the solid dielectric, since high interfacial energy will prevent through impregnation.

Freezing Point: The liquid must have a freezing point below the minimum temperature anticipated in storage or use; freezing would result in expansion which might distort the capacitor windings or container causing a short circuit and failure of the device.

Boiling Point: The liquid must not boil at the maximum expected operating temperature, and must have a maximum vapor pressure during operation sufficiently low to prevent distortion of the metal container.

Chemical Properties:

Stability: The liquid must be sufficiently stable to resist the degradation caused by extended use at high temperatures in an intense electric field and in the presence of corona discharges and active metal surfaces.

Solvency: The liquid must not cause excessive swelling of the solid dielectric.

Corrosiveness: The liquid must not react with any of the metal or non-metallic materials in the capacitor.

Toxicity:

Acute Toxicity: The liquid must have a low level of acute toxicity both for skin contact and inhalation. Contact of the liquid with humans must be expected during both the manufacturing of capacitors and due to accidental damage of the units in use.

Chronic Toxicity: The liquid must not exhibit mutagenic, teratogenic, or carcinogenic activity. Low levels of exposure over long periods of time would be expected in the capacitor manufacturing plants unless new and expensive totally enclosed manufacturing equipment were installed.

Environmental Stability: The liquid will probably enter the environment because of accidental damage of capacitors, rupture of capacitors upon failure or during material reclamation processing, or leaching from landfills used to dispose of failed or obsolete capacitors. Susceptibility to environmental degradation or biodegradation is usually not compatible with the high degree of chemical stability required to ensure successful long-term performance of the capacitor. However, if the chemical is not at least slightly degradable, it will eventually accumulate to significant levels in the environment as PCBs have done.

Bioaccumulation: Although low levels of any capacitor liquid may eventually be expected in the environment, significant health risks would probably only result from an active accumulation of the chemical in the food chain as has occurred with PCBs. A low tendency to bioaccumulate, as measured by a low octanol/water partition coefficient, would decrease the potential risk from this exposure mechanism.

5.4 Use of PCBs in capacitors

PCBs have been used in A.C. capacitors since the early 1930s. Prior to the availability of PCBs, this type of capacitor used mineral oil as a dielectric liquid. PCBs were considerably more expensive than mineral oil per gallon of liquid, but they could be used in a capacitor about half the size of a mineral oil capacitor of equivalent capacitance. Their use, therefore, resulted in much longer service life and inherent fire safety.

The use of PCBs in the manufacture of capacitors gradually decreased from 30 million pounds per year in 1965 to about 20 million pounds per year in 1975.[29] This decrease was the result of both improved capacitor designs which required less liquid dielectric and a maturing of the market for power factor correction capacitors. The demand was expected to increase considerably between 1975 and the early 1980s because of requirements of the Department of Energy for improved efficiency of electrical appliances.

In Section 6(e) of the Toxic Substances Control Act, Congress mandated an end to the use of PCBs in the manufacture of capacitors by January 1, 1979. In a separate regulatory action, the Environmental Protection Agency banned the discharge of PCBs to waterways by capacitor manufacturers after February 1, 1978, under the authority of the Federal Water Pollution Control Act (33 U.S.C. 1251 *et. seq.).*[30] The effect of this effluent standard was to encourage the early conversion of capacitor manufacturing to the use of non-PCB substitute liquid dielectrics. Since different types of capacitors have different performance requirements, it is perhaps not surprising that the various segments of the capacitor industry have had differing degrees of success in commercializing non-PCB capacitors within the tight deadlines mandated by the Federal statuatory and regulatory actions.

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(29) Versar, Inc., PCBs in the United States: Industrial Use and Environmental Distribution, Springfield, Va.: National Technical Information Service (NTIS No. PB 252 012), February 25, 1976. p. 214.

(30) Environmental Protection Agency, "Proposed Toxic Pollutant Effluent Standards for Polychlorinated Biphenyls (PCBs), Final Decision," Federal Register, Vol. 42, pp. 6531-6555 (February 2, 1977).

5.4.1 Power Factor Capacitors

There are four U.S. manufacturers of large high voltage power factor correction capacitors. All four of these companies discontinued using PCBs in this type of capacitor by mid 1977 and essentially eliminated inventories of PCB units by the end of 1977. The non-PCB capacitors now offered by these companies all perform the same electrical function, but they are constructed of different materials as is shown in Table 5.4.1-1.

TABLE 5.4.1-1

NON-PCB POWER FACTOR CORRECTION CAPACITORS

Manufacturer	Solid Dielectric	Liquid Dielectric
Westinghouse	Paper and plastic film combination	Isopropyl biphenyl
Sangamo Electric Co.	"	Phthalate ester**
General Electric	"	Phthalate ester**
General Electric	Plastic film	Phenyl Xylylethane
McGraw Edison	Plastic film	Butylated monochlorodiphenyl ether

* All of the liquid dielectric materials contain small amounts of additives as free radical scavengers, etc. The identity of these minor constituents is proprietary information.

** The phthalate ester based liquids reportedly contain a significant amount of trichlorobenzene as an additive to raise the corona extinction voltage.

5.4.2 Other Small and Low Voltage Capacitors

The development of marketable non-PCB small capacitors has been more difficult than the development of power factor capacitors for several reasons. Each of the different applications of small capacitors requires special performance characteristics which can be proved only by long-term testing.

Problems resulting from fire safety and product liability are more difficult with the small capacitors than with the large high voltage capacitors. Power factor capacitors are sold to the users (primarily utilities) directly by the manufacturers, so responsibility for product guarantees is clear cut. There would be little additional service cost to replace a failed power factor capacitor, and there is little fire hazard if a power factor capacitor should fail since most of them are located out of doors in substations or mounted on distribution poles. The small capacitors are sold as components of lighting fixtures, electrical appliances, and industrial machinery. Failure of a capacitor results in warranty claims on the manufacturer of the equipment although he may be several steps removed from the manufacturer of the capacitor. For this reason, the customers of the capacitor manufacturers are hesitant to use any new or modified type of capacitor until its satisfactory performance has been demonstrated by considerable testing. An additional problem is that many of the small capacitors are used in applications where rupture of the capacitor case following failure of the capacitor could lead to significant fire hazards.

Much of the equipment using small capacitors must be approved by Underwriters Laboratories or other national testing organizations to be commercially successful. Underwriters Labs, which is the acknowledged leader in establishing safety criteria for appliances, is requiring that non-PCB capacitors used in lighting ballasts be protected by a pressure sensitive or thermally activated circuit breaker to prevent case rupture and decrease the risk of fire.

Non-PCB small capacitors have been developed by the manufacturers who previously manufactured PCB units. These companies now have established non-PCB products for most of the applications where they previously offered PCB capacitors.

5.5 Alternatives to PCB Capacitors

PCB capacitors will not be available after mid 1979 unless EPA grants exemptions from the bans on processing and distribution in commerce of PCBs that are specified in section 6(e) of the Toxic Substances Control

Act. Therefore, replacement devices must be developed to perform the function of PCB capacitors in the future. Possible alternatives include increased use of synchronous condensers for power factor correction, the development of satisfactory dry capacitors, and the use of other dielectric liquids as replacement for PCBs in liquid-filled capacitors. The feasibility and economic attractiveness of each of these alternatives depends on the particular performance requirements of the various types of capacitors in which PCBs have been used.

5.5.1 Synchronous Condensers

Most electric motors depend on current induced in the rotor by the rotating magnetic field from the stator to provide the coupling magnetic field. Synchronous motors have the rotor winding separately energized by D.C. current through a commutator on the shaft. Therefore, the synchoronous motors are not pure inductive devices, and their apparent power factor can be adjusted by controlling the relative currents in the stator and rotor windings. If the current to the stator results in an exact balance of magnetic field strength, no current is induced from the stator windings and the motor runs at a power factor of unity. If the stator is over energized, the motor operates at a leading power factor and will perform an electrical function similar to that of a power factor capacitor.

Synchronous motors are more expensive than induction motors and require more maintenance to ensure proper adjustment of the commutator brushes. Synchronous motors provide the advantage of constant speed under varying loads, and are therefore used where close speed control is required as with drag lines used in open pit mining. Mines using equipment powered by this type of motor often depend on the motors to provide overall power factor correction for the installation and therefore do not use power factor correction capacitors.

The phase relationship in a synchronous motor depends only on the relative magnitude of the rotor and stator currents. An unloaded synchronous motor is capable of acting as an adjustable power factor capacitor, the adjustment being provided by control of the current to the rotor. If the machine is used solely for purposes of power factor correction, a shaft extension is not necessary; such a machine is known as a synchronous condenser.

The major advantage offered by synchronous condensers is that they provide completely adjustable power factor correction. In most distribution applications, the inductive load varies throughout the day as the amount of current demanded changes. Banks of power factor capacitors can provide partially responsive power factor correction if groups of capacitors are switched into and out of the circuit in response to changing requirements. However, this response will be by steps of capacitance; a synchronous condenser could provide an exact match to varying requirements. This advantage of synchronous condensers is offset by their higher maintenance requirements, higher noise levels, and much higher price. Installed cost of capacitors banks may run four dollars per KVAR, compared to an installed cost of twenty-four dollars per KVAR for synchronous condensers. Synchronous condensers are only used in those applications where their responsiveness to varying conditions justifies their higher cost. However, they can be used in place of power factor correction capacitors in almost all applications, and therefore provide a real, if expensive, alternative to the use of banks of power factor capacitors in electrical distribution systems.

5.5.2 Dry film capacitors

A major function of liquid dielectrics used in capacitors is to increase the corona resistance at points of high voltage stress such as the edge of the metal film and at rough spots and holes in the film. A liquid dielectric is not required if the capacitor is operated at a voltage below the corona discharge voltage of air. The corona discharge voltage of a dry capacitor depends both on the inherent breakdown strength of the gas (about 300 volts for air around sharp edges) and on the design of the capacitor, since voltage stress is a function of both the applied voltage and the sharpness of the edge or discontinuity.

The capacitors used with lighting fixtures and appliances in Europe and Japan have traditionally been dry film units that have not used a liquid dielectric. These capacitors have been installed so as to operate at the normal line voltage of 220 volts, which is below the voltage at which corona discharges would occur in air. To achieve equal capacitance at the normal U.S. line voltage of 110 volts would require a capacitor four times the size of that required at 220 volts. Therefore, it has been common practice in the U.S. to install the capacitors so that they operate in series with the ballast transformer or motor secondary windings and are subjected to the voltage of 330 to 500 volts usually developed at this point in the circuit. Some capacitors in high intensity lighting fixtures operate at voltages exceeding 1000 volts, although the fixtures operate at a line voltage of 110 volts.

Successful use of dry capacitors in the U.S. would require either that the electrical circuits be redesigned to lower the voltage applied to the capacitors or that the capacitors themselves be carefully designed to eliminate areas of high voltage stress. The better the design of the capacitor, of course, the higher the allowed voltage, so dry film capacitors might be developed to meet the requirements of some of the applications presently handled by liquid filled capacitors, even if the corona problem were never solved for the high voltage applications.

The most promising technology presently being developed for dry capacitors is the metalized film capacitor. In this design, the conducting plate is an extremely thin film of aluminum that has been applied to the surfaces of thin polypropylene film by vapor deposition. Polypropylene is used because it has lower dielectric losses than other thermoplastic materials. The metallized film is then thightly wound on a mandrell to exclude as much air as possible from the windings. Properly constructed small metalized film capacitors have reportedly operated successfully at voltages exceeding 300 volts. However, the construction of these capacitors requires different equipment than does the manufacture of paper/foil capacitors because of the need for a permanent core and the closer control required during the winding operation. Acceptance of metalized film capacitors for the lower voltage appliance applications is now more a matter of economics and industry practice than of unsolved scientific problems. Dry film capacitors would not be expected to take a significant portion of the market unless they were cheaper than liquid-filled units for the same applications, and there is apparently not yet sufficient difference in the potential costs of the two types of capacitors to justify the new equipment and the marketing effort required to successfully sell them.

5.5.3 Conventional Capacitors Using Non-PCB Liquid Dielectrics

The Toxic Substances Control Act established a deadline for ending the manufacture of PCBs, and consequently, the capacitor manufacturers were faced with the immediate need to develop acceptable substitutes for their entire lines of PCB capacitors within a period of one to two years. General electric already had experience in using phthalate esters as a replacement for PCBs in capacitors manufactured for export to Sweden and Japan where the importation of PCBs was banned in the early 1970's. Substitutes for PCBs had been fairly well developed in Japan in the four or five years after the government banned the use of PCBs, and it was therefore apparent that non-PCB capacitors could be built without major changes in manufacturing technology or equipment by using suitable substitute liquid dielectrics. The substitute materials presently being used all have lower dielectric constants than PCBs, so the non-PCB capacitors are all somewhat larger than the PCB units they replace. In addition, the non-PCB liquids are all more flammable than PCBs, so additional features have been necessary to protect against rupture and fire of failed non-PCB units used in appliances and other inherently hazardous applications.

Although many different liquids have been used in capacitors, including castor oil and mineral oil, there are only a few chemicals that have sufficient chemical stability and suitable electrical properties to be used successfully in capacitors as a direct substitute for PCBs. The electrical and physical properties of PCBs and several of the more promising substitute materials are summarized in Table 5.3.3-1.

TABLE 5.5.3-1

Properties of Capacitor Dielectric Liquids

Chemical	Bis(2-ethylhexyl) Phthalate	Diisononyl Phthalate	Butylated Monochlorodiphenyl-Ether*	Isopropyl Biphenyl **	Phenyl Xylylethane ***	PCB (Aroclor 1016)
Electrical Properties						
Dielectric Constant	5.33	4.66	4.4 to 4.8 (20°C) 3.2 to 3.4 (85°C)	2.83 (25°C)	2.6 (25°C)	5.85 (25°C) 4.85 (100°C)
Dielectric Strength	28 KV	30 KV	45 KV	45 KV	60 KV	35 KV
Dissipation Factor	.14	.05	.04 max	.002		.0025
Resistivity ohm-cm	2×10^{11}	3×10^{10}	34×10^{12} (26°C)	1×10^{11}	1.0×10^{14}	5×10^{11}
Physical Properties						
Specific Gravity	0.99		1.09	0.988 (25°C)	0.988	1.362
Viscosity	81 cps (20°C)	95 cps (20°C)	10.5 cs (30°C) 14 cs (25°C)	4.9CS (38°C) 20CS (25°C)	6.5 cs (30°C)	71 to 81 SUS (100°F)
Pour Point	-50°C	-48°C	<-45°C	-51°C	-47.5	-19°C
Surface Tension			40 dynes/cm			
Expansion Coefficient			7.4×10^{-4} cc/cc/°C			6.8×10^{-4} cc/cc/°C
Flashpoint	218°C	221°C	174°C	140°C	155°C	141°C
Firepoint	246°C	257°C	199°C	165°C	160°C	None
Corrosivity			Non-corrosive			

TABLE 5.5.3-1 (Cont'd)

Properties of Capacitor Dielectric Liquids

Chemical	Bis(2-ethylhexyl) Phthalate	Diisononyl Phthalate	Butylated Monochlorodiphenyl-Ether*	Isopropyl Biphenyl **	Phenyl Xylylethane ***	PCB (Aroclor 1016)
Toxicity						
Acute:						
Oral	LD50: >128g/kg (Mouse) LD50: 31g/kg (rats)	>10g/kg (rat)	>10 g/kg. (rats)	LD50: 8.5g/kg (rats)	LD50: 1.7 or 2.3 g/kg (rats)	
Dermal			No effect (rabbits, guinea pigs)	Slight irritation (rabbits)	>5 ml/kg	
Inhalation			No effect (rats)	Slight effect (920 ppm, rats)		
Chronic:						
Mutagenicity			No effect (Ames test)	No effect (Ames test)	No effect (Ames test)	Yes
Teratogenicity	Yes (rats)		No effect (Rat, Rabbits)		No effect (mice, rats)	Yes
Bioaccumulation:	1/500 times PCBs		1/22 times PCB		<.1 value for PCB	
Excretion Rate:			50% in 11 hours (monkey and rats)			

*Commercial mixture of mono-, di-, and tri sec butyl derivatives manufactured by Dow Chemical Co.

**Commercial mixture of 95% mono- and 5% di- and tri- isopropyl biphenyl trademarked Suresol 250 and manufactured by Sun Petroleum Products Co.

***Nisseki Condenser Oils or Nisseki Hisol SAS manufactured by Nippon Petrochemicals.

The impregnation of a capacitor with a liquid dielectric requires that the air be removed by establishing a vacuum and that the solid dielectric wick the liquid into the windings of the capacitor. Polypropylene cannot be used as a direct replacement for the kraft paper used as the solid dielectric/spacer in conventional small capacitors because it is solid and therefore does not act as a wicking agent and because it is not wetted by most liquids. Development of a completely new technology may eventually allow use of synthetic dielectric materials in small film/foil capacitors. Sandia Laboratories has demonstrated the feasibility of a metalized film capacitor using a perfluorcalkane liquid (at $200 per gallon) as the dielectric liquid. Large high voltage power factor capacitors using all film (polypropylene) construction are presently being manufactured by McGraw Edison and by General Electric. The McGraw Edison units use alkylated monochloro biphenyl ether as the liquid dielectric. The General Electric all-film capacitors use 1,1-phenyl xylylethane as the liquid dielectric

The present state of technology in the production of commercial capacitors is based mainly on the methods used to produce PCB capacitors. The following sections discuss the chemicals that are presently finding wide use as substitutes for PCBs in the U.S., or that are being considered for use in this application. Most capacitor manufacturers also add small amounts of additives to the liquid which act as antioxidants, corona suppressants, etc. These other chemicals are usually present in concentrations of no more than a few tenths of one percent.

5.5.3.1 Alkyl Phthalates

Alkyl phthalates, such as bis(2-ethylhexyl) phthalate and diisononyl phthalate, are being used as the basis for the dielectric liquid in all small capacitors that previously used PCBs and in some of the large power factor capacitors that have been manufactured by Sangamo and General Electric.

Total U.S. production of phthalate esters was 382,501 metric tons in 1976. Over 95% of the phthalate esters are used as plasticizers, particularly in polyvinyl chloride resins in which the phthalate ester may account for up to 40% of the weight of the material. Stanford Research Institute estimated that over 53,000 metric tons of phthalates were used as plasticizers for plastics in electrical equipment in 1976. A major electrical use of phthalates is as a plasticizer in vinyl resins used as wire and cable insulation.

Approximately 30 different phthalate esters are manufactured in the United States. The material produced in the greatest amount is bis(2-ethylhexyl) phthalate, comprising 35% of the 1976 production. This material is produced at nine different plants in the U.S.

The phthalate esters are noted for their low acute toxicity. Although laboratory tests have demonstrated that bis(2-ethylhexyl) phthalate is teratogenic and mutagenic in mammals at high dosages, the relevance of chronic biological effects at low dose rates has not been assessed.[30] In rats, teratogenic effects of bis(2-ethylhexyl) phthalate include fetal resorptions, gross abnormalities, and decreased fetal weights. Effects on mice include a pronounced decrease in fertility, an increase in early fetal deaths, and reduced numbers of fetal implants.[31]

The only substantiated health effects caused by long-term work place exposure to phthalate esters have been occasional cases of mild skin irritation. Industrial workers exposed to phthalate vapors or aerosols at ambient levels of 10 to 66 mg/m^3 were observed by Milkov.[32] Duration of occupational exposure ranged from 6 months to 19 years. The most frequent complaint by the workers was pain in the upper and lower extremities, accompanied by numbness and spasms. Studies of the nervous system revealed polyneuritis increased with length of the

(30) Autian, John, "Toxicity and Health Threats of Phthalate Esters: Review of the Literature" Environmental Health Perspectives, June 1973, pp. 3-26.

(31) Environmental Protection Agency. Criteria and Standards Division. Draft Water Quality Criteria Document for Phthalate Esters. March 2, 1978.

(32) Milkov, L.E., et. al. "The status of health of workers subjected to the effects of phthalate plasticizers in the production of artificial leather and film (with PVC base)" [translated title] Gig. Tr. Prof. Zabol. 13, 14 (1969) as cited in: Peakall, David B. "Phthalate Esters: Occurrence and biological effects," Residue Reviews Vol. 54 (p. 1) 1975.

employee's service. Functional disturbance of the nervous system was noted in fifteen percent of the workers.[33] However, these workers were also exposed to vapors from phosphate ester plasticizers and to vinyl chloride. Both of these chemicals are known to produce the health effects noted in the workers, so this study does not prove that phthalates are toxic.

The phthalates may enter the environment by slowly leaching or volatilizing from plastic resins and by direct discharges by manufacturers and users. Because the phthalates have low solubility in water and high solubility in fat, environmental levels of phthalates will bioaccumulate in fish and mammals. Bis(2-ethylhexyl)phthalate has been found to bioaccumulate in fathead minnows to concentrations 115 to 886 times the concentration in water.[34] Phthalates are known contaminants in both drinking water and food (33, pp. 19, 20; 35). However, the amounts of phthalates present in food have not been found to be toxicologically significant.[36] Although the phthalates are stable in their industrial uses, they have been shown to be biodegradable in soil and water.[37] Phthalate esters are listed as toxic pollutants under section 307(a) of the Clean Water Act, and the Interagency Toxic Substances Testing Committee has recommended additional environmental effects testing for phthalates.

Diisononyl phthalate has been promoted as a liquid dielectric primarily by Exxon Chemical Co. under the tradename ENJ-2065.[38] As noted in Table 5.5.3-1, this liquid has a lower dielectric constant than bis(2-ethylhexyl) phthalate, but it also has a significantly lower loss factor, and a higher dielectric strength.

(33) Environmental Protection Agency. Criteria and Standards Division. Draft Water Quality Criteria Document for Phthalate Esters. March 2, 1978.
(34) Mehrle, P.M. and F.L. Mayer. 1976. Di-2-ethylhexyl Phthalate: Residue Dynamics and Biological Effects in Rainbow Trout and Fathead Minnows. Columbia, Missouri: Fish and Pesticide Research Laboratory.
(35) Environmental Protection Agency. 1975. Preliminary Assessment of Suspected Carcinogens in Drinking Water. EPA/560/4-75-003. p. 9.
(36) Food and Drug Administration. 1974. Compliance Program Evaluation, FY 1973 Phthalate Esters in Fish Survey (7308.07A). Washington, D.C.: Bureau of Foods, Food and Drug Administration, Nov. 15.
(37) Englehardt, G.; P.R. Wallnöfer; and O. Hutzinger. 1975. "The Microbial Metabolism of Di-n-butyl Phthalate and Related Dialkyl Phthalates," Bulletin of Environmental Contamination and Toxicology, Vol. 13, pp. 342-347.
(38) Inchalik, E.J. (Exxon Chemical Co.) "ENJ-2065-An Electrical Insulating Fluid" in Conference Proceedings, National Conference on Polychlorinated Biphenyls (EPA-560/6-75-004), March 1976. pp. 334-337.

The particular chemical composition of dielectric liquid used in capacitors is kept a trade secret by each company, so the total consumption of each of the different types is not known. However, it is likely that most of the material used is either bis(2-ethylhexyl)phthalate or diisononyl phthalate. It is known that General Electric adds a substantial quantity of chlorinated benzene to the phthalate ester in their Dielektrol-II high voltage power factor capacitors to increase the corona resistance of the liquid. Sangamo Electric reportedly uses a similar mixture in the power factor capacitors that they manufacture.

Total consumption of PCBs by the capacitor manufacturing industry never exceeded 20 million pounds per year of which 55% was used in small capacitors and 45% in power factor capacitors. Although the non-PCB capacitors are larger than the equivalent PCB units because of the lower dielectric constants of the substitute materials, the phthalate esters weigh less per gallon than do PCBs, so the total weight used is probably the same or less for the substitutes than for PCBs. Even if the consumption of phthalates as capacitor dielectric liquids were to total 20 million pounds per year, this would be a small fraction of the total production of this type of chemical and would still be less than 20% of the amount used as a plasticizer in wire and cable insulation. Since the capacitor liquids are totally sealed in metal cans, there is no chance for leaching or volatilization to occur while the units remain intact. Therefore, the amount of phthalates introduced into the environment from capacitors would be expected to be a small fraction of the amount lost to the environment from other electrical uses, and a negligible fraction of the total amount dispersed from plasticizer applications.

5.5.3.2 Isopropylbiphenyl

Isopropylbiphenyl is presently being used by Westinghouse as a dielectric liquid in high voltage power factor capacitors. The solid dielectric used in these capacitors is reportedly a composite of kraft paper and polypropylene film. The liquid sold by Sun Petroleum Products Co. for use as a capacitor dielectric has the trade name Suresol 250 and contains 95% mono- and 5%

isopropylbiphenyl. A mixture of 75% mono- and 25% di- and tri- isopropylbiphenyl is sold as Suresol 245 and is extensively used as the dye carrier in carbonless copy paper, an application in which it replaced the previously used PCBs in 1972.

Isopropylbiphenyl has a fairly low dielectric constant (2.5 at 25°C) but has other attractive electrical properties including high dielectric strength, high resistivity, and low dissipation factor. The high voltage power factor capacitors that use this liquid as the dielectric presumably are designed to operate at higher voltage stress levels than are similar capacitors using other liquids to take advantage of the high dielectric strength and thereby achieve high capacitance without increasing the plate area and the size of the unit.

The commercial mixture used in capacitors has a low degree of acute toxicity (14 day rat LD_{50}= 8.5 g/kg body weight)[39] and significant cumulative properties.[39] Isopropylbiphenyl is mildly to moderately irritating to the skin. The material has been found not to be mutagenic as determined by the Ames test. The material can be disposed of by incineration and is rapidly biodegraded by soil and water microorganisms.

5.5.3.3 Butylated Monochloro Diphenyl Ether

Dow Chemical Company markets a capacitor dielectric liquid which consists of a mixture of monochlorobiphenyl ethers of varying degrees of butylation.[40] The material consists mainly of mono-, di-, and tri-sec-butyl derivatives. This material is used by McGraw Edison in film/foil high voltage power factor (shunt) capacitors that are used by electrical utilities in power distribution systems. McGraw Edison refers to the material by the trade name Edisol.[41]

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(39) Volodchenko, V.A.; E.R. Sadokha; and V.D. Yaremenko. 1973. "Toxicity of Isopropyldiphenyl," Farmakol. Toksikol, No. 8, Kiev, pp 183-4. (in Russian).

(40) Dow Dielectric Fluid - C4, (Form 176-1347-78) Midland, MI: Dow Chemical U.S.A., 1978.

(41) Lapp, John, (McGraw Edison Company), A New Dielectric Fluid for Power Capacitors, Bulletin No. 76045, Cannonsburg, Pa.: McGraw Edison Co., October 1976.

Although polypropylene film has a lower dielectric constant than kraft paper, it also has a higher dielectric strength and lower loss factor than paper and is available in thinner films. The liquid dielectric used in all-film capacitors should have a dielectric constant close to that of the film, and be able to wet the film without dissolving in it or causing excessive swelling of the film. The liquid used by McGraw Edison has the proper physical and electrical properties for successful performance in all-film high voltage A.C. capacitors: dielectric constant = 3.2 at 80°C vs about 2.0 for polypropylene film; solubility of polypropylene in liquid less than 60 ppm; contact angle of fluid on polypropylene = 15° compared to trichlorobiphenyl at 48°.

Dow Chemical Company has reported considerable health and environmental data on this material including:

Toxicity:

Mammal -

Acute oral	10 g/kg	rat
Dermal	No effect	rabbits, guinea pigs
Inhalation	No effect	rats (saturated air at 50°C)
Subchronic	No effect	5 mg/kg/day, rats

Fish -

Subchronic	Does not induce hepatic MFO enzymes in trout(42)

Chronic Toxicity:

Mutagenic	No effect	microbial—Ames Test
Teratogenicity	No effect	rats and rabbits

Biodegradation:

45 times PCB rate

Bioaccumulation:

298 ± 70 ratio trout muscle to water

Excretion rate:

50% in 24 hours from trout
50% in 11 hours from monkeys and rats

(42) Addison, R.F., and F.C.P. Law. "Induction of Hepatic MFO Enzymes in Trout Fed PCB, Some Proposed PCB Replacements, and Related Compounds," Abstracts of 18th Annual Meeting, Society of Toxicology, New Orleans, March 11-15, 1979. Paper No. 365.

The Dow Chemical dielectric fluid is chemically a mixture of aromatic halo ethers. This class of chemical is listed as a toxic pollutant under section 307(a) of the Clean Water Act. Dow Chemical has petitioned EPA to have this class of chemical removed from the list. EPA has recently published a review of the available data as part of its response to this petition.[43] This material has a lower dielectric constant than the phthalate esters and is more expensive than the phthalates. The use of this material is limited so far to the large high voltage capacitors that use all film solid dielectrics. It has not been used as a direct substitute for PCBs in conventional paper/foil small capacitors.

5.5.3.4 1,1-Phenyl Xylylethane

Nippon Oil Co. has been manufacturing 1,1-phenyl xylylethane (PXE) in Japan since 1972 as a substitute for PCBs in carbonless copy paper and in capacitors. Production of PXE has been several thousand metric tons per year.[44] The material reportedly has a short biological half-life, is not very accumulative, and is easily biodegradible.[45] Use of PXE in Japan since 1972 has not resulted in any measurable levels of PXE in the environment.[44] PXE is sold in Japan under the trade names "Nisseki Hissol SAS" (solvent grade) and "Nisseki Condenser Oil S" (capacitor grade).

In December, 1978, General Electric announced the availability in the U.S. of a new line of all-film/foil power factor capacitors which use PXE as the major constituent of the dielectric liquid.[46] The G.E. trademark for

(43) Environmental Protection Agency. "List of Toxic Pollutants: Petition to Remove Aromatic Haloethers," Federal Register Vol. 44, No. 60 pp. 18279-83, March 27, 1979.

(44) Sumino, K. 1977. "Mass Fragmentgraphic Determination of Diisopropyl Napthalene and Phenyl Xylylethane, and the Environmental Contamination from Them," Archives of Environmental Contamination and Toxicology. Vol. 6, pp. 365-369.

(45) Hasegawa, H; M. Sato; and H. Tsuruta. 1973. "Special Report on the Effects of Human Health and Chronic Toxicity of PCB and Other Pollutants, to Prevent the Pollution from Them: Study on the Toxicity of Alternatives for PCB," Science and Technology Agency of Japan, p. 139 (as cited in Sumino 1977).

(46) General Electric. 1978. Film/Foil Power Capacitors (GEA-10600 9/78 (10M)) Capacitor Products Department, General Electric, Hudson Falls, N.Y.

this dielectric liquid is Dielektrol III. G.E. has apparently achieved complete impregnation by the liquid through a process of treating the polypropylene film to form a matted surface (trademarked Hazy film) and by embossing the aluminum foil to provide channels for liquid movement. G.E. claims that this new film/foil capacitor reduces electrical operating losses from 0.5 watts per KVAR for the previously used paper/film/foil/PCB design to less than 0.3 watts per KVAR. In addition to reducing distribution losses and the resulting demand on generating capacity, this reduction in operating losses means that the capacitors will generate less heat and will operate at a lower temperatures, thereby increasing their service life. G.E. also claims that this design of capacitor will form a lower resistance short circuit when it fails than will a paper/film/foil design capacitor. As a result, the circuit breaker will act faster with the new design, reducing the time for buildup of pressure within the case and reducing the probability of case rupture.

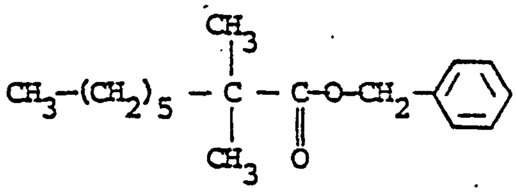
5.5.3.5 Other Capacitor Dielectric Liquids:

Most of the recently reported research on the development of substitutes for PCBs has involved chemicals that could be added to isopropylbiphenyl to increase its dielectric constant. Two types of chemicals described in patents issued to Monsanto are ketones and diaryl sulfones. One patent describes the use of a liquid dielectric material consisting of 52.8% dimethvlbenzophenone, 46.9% isopropylbiphenyl, and 0.3% 3,4-epoxycyclohexylmethyl, 3,4-epoxycyclohexanecarboxylate. Aluminum foil/paper capacitors impregnated with this mixture reportedly had slightly higher loss factors and capacitance ratings than similar control capacitors impregnated with PCBs. The PCB capacitors failed after 188 hours at 1000 volts and 100°F, but the other did not.(47) U.S. patent describes a mixture of 10-30% tolyl xylyl sulfone, 70-90% isopropylbiphenyl, and 0.1-0.3% of the same stabilizer.(48) The sulfones generally

(47) Munch, Ralph H. (Monsanto Co.) Dielectric Impregnating Agents for Capacitors, Ger. Offen. 2,452,213, May 7, 1975.
(48) Munch, Ralph H. (Monsanto Co.) Dielectric Composition for Impregnating Electric Capacitors, U.S. Patent 3,948,788, April 6, 1976.

are noted for high dielectric constants and fairly high loss factors: phenyl xylyl sulfone has a dielectric constant of 29.0 at 25°C, and a loss factor of 6.3%.[49] Monsanto reportedly furnished sulfone based dielectric liquid to several capacitor manufacturers under the trade name MCS-1238, and the material performed well on test.[50] However, Monsanto later decided against commercial development of these materials because they could not be cost competitive with phthalate ester based dielectric liquids.

Another chemical that is presently being marketed in the U.S. as a possible capacitor dielectric liquid is benzyl neocaprate, which is produced by Prodelec (France) under the trade name BNC. This material is essentially a C_{10} acid that has been reacted with benzyl alcohol and has the following structure:



This material reportedly has a dielectric constant of 3.2.

Other materials that have previously received serious consideration as possible liquid dielectrics are chlorinated diphenylethers and 1,3,3 trimethyldichlor 1 phenyl indane. The physical and electrical properties of these materials are summarized in Table 5.5.3.5-1.

(49) Clark, Frank M. Insulating Materials for Design and Engineering Practice, New York: John Wiley & Sons, 1962, p. 395.

(50) Wood, David, "Chlorinated Biphenyl Dielectrics - Their Utility and Potential Substitutes" in Conference Proceedings, National Conference on Polychlorinated Biphenyls. EPA-560/6-75-004, March 1976, pp. 317-322.

Table 5.5.3.5-1

Properties of Potential Capacitor Dielectric Liquids.*

	Chlorinated diphenyl ethers monochloro	Chlorinated diphenyl ethers pentachloro	1,3,3 tri methyl dichlor 1 phenyl indane
Electrical Properties			
Dielectric Constant	4.5 30°C 3.8 100°C	5.0 30°C 4.3 100°C	6.0 (0°C) 5.0 (120°C)
Dielectric Strength	35 KV	35 KV	35-45 KV
Dissipation Factor			<.001 (10 to 60°C) <.01 (-10 to 120°C)
Resistivity ohm-cm	1.5×10^{11} (30°C)	1×10^{12} (30°C)	5×10^{13} (40°C)
Physical Properties			
Specific Gravity	1.18	1.53	1.14
Viscosity	36 (38°C)	390 (38°C)	62SSU (93°C)
Pourpoint	-55°C	0°C	8°C
Flashpoint			185°C
Firepoint	146°C	None	250°C
Corrosivity	Neutral	Neutral	Neutral

*Source: Clark, Frank M., Insulating Materials for Design and Engineering Practice, New York: John Wiley & Sons, 1962. pp. 205-208.

PCBs were banned in Japan in 1972, and since then the Japanese manufacturers have used a number of different liquids in addition to PXE including 1,1-di (monochlorophenyl) ethane, alkyl naphthalene (trade name KMC), silicone oil (trade name KSK, manufactured by Kureha), and an aromatic hydrocarbon material (trade name KIS, manufactured by Kureha). None of these materials have been used in the U.S. as a substitute for PCBs.

Capacitors designed for use at higher frequencies (i.e., 1000 hz and above) have traditionally used liquids other than PCBs. Both mineral oil and castor oil are sometimes used in special applications. However, the most commonly used material is chlorinated naphthalene, which is used in automobile ignition capacitors.

Chlorinated naphthalenes are similar to PCBs in that they are available as mixtures with different degrees of chlorination and are noted for their chemical stability and toxicity. The major use of chlorinated naphthalenes in the U.S. is as an impregnant in automotive capacitors, which use a mixture of trichloro and tetrachloro naphthalenes. This material is a solid at room temperature and has a melting point of 93 to 115°C, depending on the particular mixture that is used. The dielectric constant of the capacitor grade material is 4.1. Chlorinated naphthalenes have not been used in the U.S. as a substitute for PCBs in A.C. capacitors because of their high power factor at low frequencies (0.37 at 60 hz, 100°C),[51] and because they are solids that can develop cracks while in use, resulting in increased corona discharges.

It is unlikely that chlorinated naphthalenes will be used in A.C. capacitors. The toxicity of this material is well documented,[52] and the monochloro naphthalene which could perhaps be used as the basis of a liquid dielectric is presently listed by the EPA as a priority pollutant.

(51) Kover, Frank D., (Environmental Protection Agency), Environmental Hazard Assessment Report: Chlorinated Naphthalenes, Springfield, Va.: National Technical Information Service (PB-248-834), December, 1975.

(52) Koppers Co., Inc. Halowax Chlorinated Naphthalene Oils and Waxlike Solids, (CM-203-770), Pittsburgh, Pa.: undated.

6.0 CONCLUSIONS

PCBs gained widespread use from 1930 until 1978 because of their chemical stability, attractive electrical properties, and availability in a range of melting points and viscosities. It was the same properties of chemical stability and low water solubility that resulted in their environmental persistence and bioaccumulation.

The materials used as substitutes for PCBs are less stable chemically, which results in increased fire risk but which also ensures that they are less persistent in the environment. Because the use of PCBs sensitized the users to problems of acute and chronic toxicity, the materials that have been selected as substitutes for PCBs have notably low toxicity and well defined environmental fates. The switch from PCBs to substitute materials has required a certain degree of redesign of equipment in order to maintain adequate fire safety while using more flammable liquids. However, the electrical equipment manufacturers have developed non-PCB equipment that performs adequately in almost every application where PCBs were previously used. The banning of PCBs as a base for transformer askarel coolant liquids led to the development of specifications for high fire point transformer liquids and the increased use of various liquids meeting these specifications, including natural and synthetic hydrocarbons and silicone oils. These same liquids are suitable for use in electromagnets. In those applications where absolute fire protection is required, dry air-cooled transformers and magnets are now available, and engineering changes are usually available that will allow the safe use of less expensive oil-cooled units.

The development of adequate fire safety in small capacitors using phthalate esters instead of PCBs required the development of circuit breaker devices within the units that could sense either pressure or temperature increases. The capacitor manufacturers all managed to develop non-PCB replacements for the major items in their product lines, and no major market shifts have occurred. Of course it is still too early to state that the transition away from PCBs was achieved without any problems, and indeed some problems in product life and performance might be expected to appear as non-PCB capacitors remain in service for longer times. The previous change in capacitor dielectric liquid occurred in 1972 when the industry switched from Aroclor 1242 (42% chlorine) to Aroclor 1016 (40% chlorine), and it was several years before all of the performance problems were solved.

The switch from PCBs to substitute liquids has not been accomplished without a great deal of effort by the manufacturers who have been faced with a legislated cutoff date for PCBs. Money has been invested and risks taken on product changes that were made on engineering judgement and that could not wait for the results of long-term field testing. It is to the credit of the electrical equipment manufacturers that they have made this change with apparent success.

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SHEET | EPA 560/6-77-008

4. Title and Subtitle Assessment of the Use of Selected Replacement Fluids for PCBs in Electrical Equipment

5. Report Date March 1, 1979

6.

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11. Contract/Grant No. 68-01-3259

12. Sponsoring Organization Name and Address
Office of Toxic Substances
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Washington, D.C.

13. Type of Report & Period Covered
Final Task Report

14.

15. Supplementary Notes
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16. Abstracts
This report summarizes the required physical and electrical properties of liquids used as dielectric and cooling fluids in transformers, electromagnets, electric motors, and capacitors. Prior to 1977, PCBs were widely used in all of these applications and provided excellent fire safety. The use of PCBs was banned by the Toxic Substances Control Act. The new materials that were developed as substitutes for PCBs in these applications are discussed in light of the required properties and the performance trade-offs that resulted from their use.

17. Key Words and Document Analysis. 17a. Descriptors

Polychlorinated Biphenyls
PCBs
Capacitors
Transformers
Silicones
Phthalates
Aromatic Compounds
Indenes
Hydrocarbons
Chlorohydrocarbons
Chlorinated Aromatic hydrocarbons

17b. Identifiers/Open-Ended Terms

17c. COSATI Field/Group

18. Availability Statement
Release Unlimited

19. Security Class (This Report) UNCLASSIFIED

20. Security Class (This Page) UNCLASSIFIED

21. No. of Pages 106

22. Price

FORM NTIS-35 (REV. 10-73) ENDORSED BY ANSI AND UNESCO. THIS FORM MAY BE REPRODUCED USCOMM-DC 8265-P74