SUBSTITUTES FOR PCBs

STATUS AND PROSPECTS

INTRODUCTION

Current consumption of PCBs by U.S. industry (1974) is as follows:

	PCB lb/year	Units/year
Electrical Capacitors	22.0 million lb	100 million capacitors
Electrical Transformers	11.2 million lb	5000 transformers
Investment Casting Wax	.4 million lb	1.2 million lb wax

CAPACITORS

PCBs are used in capacitors because of their unique electrical properties and good resistance to fire. Electrical capacitors containing PCBs are included in nearly every fluorescent light, television set, and air conditioner that is built in the United States. Larger capacitors are used in industry to assure the efficient distribution and use of electrical energy.

A number of substitutes for PCBs have been developed and are being tested. The important properties of each of these materials are summarized in the following Table. Sufficient data should be available within one to three years to determine whether the use of any of these alternative fluids will be warranted based on an analysis of combined health and fire risks.

The PCBs currently being used in capacitors were reformulated in 1971 to have similar use properties with minimum achievable ecological persistence. The adverse environmental effects of PCBs are well documented, and the environmental load anticipated from continued production of PCB capacitors will be small compared to the load arising from past uses of PCBs. The present substitutes for PCBs in capacitors have largely not been tested for long term health effects. Most potential substitutes would apparently increase the risk of fire in consumer and industrial electrical equipment. However, several of the substitutes are in commercial use in foreign-made capacitors and in U.S. produced equipment for foreign markets.

MONS 045543

Relative Merits of Substitutes for PCB in Capacitors

	System Cost vs PCB	Fire Resistance	System Compatibility*	Short Term Toxicity	Long Term Toxicity and Environmental Effects	Availability
Mineral Oil	2X	Poor	Poor	Good	Good	OK
Phthalate esters EXXON	1.1X	Poor-fair	Good	Fair	Questionable	Used now in Japan
Isopropyl dichloro biphenyl	1.1X	Fair-good	Good	Fair	Questionable	On test in France
Silicones DOW, GE, UK, STF	1.2X	Fair	Good	Excel.	Excellent	To be introduced in 1976
Butylated monochloro diphenyl oxide DOW	1.1X	Fair-good	Good	Fair	Questionable	On test in U.S.
Synthetic hydrocarbon oils	1.1X	Poor	Good	Good	Questionable	Lab tests at present
Solid plastic film	3X	Good	No	Excel.	Excellent	3 to 5 years

*Compatibility is the ability to use replacement capacitors in existing systems - as a function of physical/dimensional constraints.

MONS 045544

TRANSFORMERS

Electrical transformers are used in the distribution of electricity to minimize the losses of power between the generator and the user. These transformers are filled with an oil to absorb the heat which is generated inside the transformer. The transformers are normally enclosed; however, in the event of a short circuit or other failure, the oil can spill. Approximately 90 per cent of all transformers are located away from buildings and do not present a fire hazard; any fire would be limited to the transformer itself. These transformers are filled with mineral oil which is completely satisfactory except for its flammability.

The remaining 10 per cent of all transformers are located within buildings where fires would be very hazardous. These transformers are filled with a non-flammable liquid containing 60 per cent to 70 per cent PCBs. If these transformers had been located outside the building or provided with a fireproof vault, the initial installation cost would have been $5,000 to $50,000 higher for each transformer.

Recently, silicone oils have been proposed as substitutes for PCBs in transformers in hazardous locations. These silicone oils are flammable, but much less so than mineral oil. The decision as to the replacement of PCB with silicones must be based on a decision as to whether the increased risk of fire offsets the reduction in toxicity achieved with the silicones. Silicone oils are currently being used in Japan in railroad locomotive transformers.

There are no technological barriers to the complete elimination of PCBs in transformer applications. However, the alternatives all incur economic penalties:

Alternative Action	Cost
Locate transformer in safe location - new installation	$5,000 to $50,000
Locate transformer in fire proof vault	$5,000 to $50,000
Use air cooled transformer	1.5 times as expensive; noisy; not as reliable
Use silicone oil - new installation	1.2 times as expensive; unknown increased fire risk
Convert from PCB to silicone oil	$450 to $15,000

INVESTMENT CASTING

Decachlorobiphenyl ("deka") is used as a pattern wax filler in investment casting. About 400,000 lb is imported annually by one wax manufacturer; and about 1,200,000 lb/year of was containing deka wax is produced (unit price about $0.70/lb; yearly sales approximately 0.8 to 1.0 million dollars). Details of the production process are not known. The manufacturer of the deka wax also produces other pattern waxes which presumably contain chlorinated terphenyls (PCTS) as fillers.

Substitutes for the deka PCBs can be either a replacement filler material or an unfilled wax. Properties required for a filler are: melting point over 300°C, high heat transfer coefficient, low thermal coefficient of linear expansion, and minimum ("zero") ash. Isopthalic acid is a promising filler candidate and has been used to a limited extent, but the grade used did leave an ash residue. A new grade, only recently commercialized, exhibits much lower ash and metal contents. Its costs is $0.35/lb, which is comparable to or lower than PCB.

Prior to the use of PCBs or PCTs as fillers, unfilled waxes were used. Industry claims that reverting to the use of unfilled waxes would increase production costs by about 10 per cent. However, new types of unfilled waxes have recently entered the market, and it is claimed that their properties are equivalent to the filled wax and their cost is slightly lower ($0.60 to $0.65/lb). Although the exact formulation of these waxes is not known, they reportedly contain no chlorinated additives.

In summary, technically adequate substitutes appear to be available for decachlorobiphenyl filler in pattern waxes. Maximum increases in costs would be about 10 per cent. The only producer of wax containing PCBs could probably change to other types with very little technical difficulty or economic impact.

TOXICITY OF POTENTIAL SUBSTITUTES

Very little information appears to be available concerning effects of long-term exposure to most of the potential substitutes mentioned. Mineral oil and silicone oil would appear to be the least likely to cause toxic effects, but mineral oil sometimes contains aromatic compounds and little is known about the degradation products of silicones. Phthalic acid and phthalates have apparently not been studied in depth. In addition, little is known about the long-term toxicity of decachlorobiphenyl. and PCTs.

include the diphenyloxides as having no information

5.0 SUBSTITUTES FOR PCBs IN THE ELECTRICAL EQUIPMENT INDUSTRY

Polychlorinated biphenyls (PCBs) were first manufactured commercially in 1929. In the United States, PCBs have been manufactured by a single producer, the Monsanto Industrial Chemicals Company in recent years.

In 1970, Monsanto announced a program that, since 1972, has led to a total restriction on sales of PCBs for all uses except the manufacture of sealed electrical equipment, specifically capacitors and transformers. As a result, there are currently about 25-30 direct customers who are using PCBs to manufacture "Closed Electrical Systems" or are in the course of servicing these systems.

Newly obtained information from industry sources indicates that near term replacement of PCBs in most closed electrical service is not technically feasible since there appear to be no substitutes which could provide the safety, reliability and economics of PCBs. The development of satisfactory substitutes for PCBs in these applications must be based on a thorough understanding of the requirements of the electrical services and of the properties of PCBs which make them uniquely desirable.

5.1 Capacitor Dielectric Fluids

In order to set the proper framework in which to describe the required properties of the materials that are used in the construction of capacitors, and therefore the nature of the substitutes that might be used in place of PCBs, it is appropriate to briefly discuss the nature of capacitors, the reasons they are used, and the resulting electrical characteristics of such a device.

5.1.1 Industrial Uses of Capacitors

Oil filled capacitors are used in electrical equipment to compensate for inductive loads imposed by other circuit components (power factor correction) and to provide a shift in the phase relationships between voltage and current in motor starting circuits.

5.1.1.1 Power Factor Correction. The largest use of oil filled (PCB) capacitors is to increase the efficiency of electrical power distribution by correcting for the power factor of inductive machinery such as industrial motors and fluorescent light transformers (ballasts). In general, the load imposed on a power line by these electrical devices is not purely resistive, but is also partly inductive. The voltage drop across such an inductor is proportional to the rate of change of current through the device; hence

$$V_L = -L \frac{di}{dt}$$

where the negative sign expresses the reaction of the inductance to a change in current through the inductance. If the current is expressed in the form

$$i = i_o e^{j\omega t}$$

where $j \equiv \sqrt{-1}$, $e^{j\omega t} = (\cos \omega t - j \quad \omega t)$, $\omega = 2\pi f$, f = frequency.

Then

$$v = j\omega L\, i = Zi$$

where Z is the inductive reactance given by

$$Z_L = j\omega L . \qquad (1)$$

On the other hand, for a capacitance C, the potential difference

$$V_C = \frac{Q}{C} = \frac{\int i\, dt}{C} = -\frac{1}{j\omega C} \quad i .$$

Hence, the capacitive reactance Z_C is given by

$$Z_C \equiv -\frac{1}{j\omega C} . \qquad (2)$$

In the event that a series circuit, containing inductive (L), capacitance (c), and resistive (R) elements, has a potential difference $v = v_o e^{j\omega t}$

across it, the relation between current and applied potential difference is given by

$$L\frac{di}{dt} + Ri + \frac{1}{C}\int i\,dt = V_o e^{j\omega t} \quad . \tag{3}$$

A solution of this equation is in the form

$$i = i_o e^{j(\omega t + \sigma)}$$

where σ expresses the possibility of there being a phase difference between the applied potential difference and the resulting series circuit current. On substitution of the assured solution into the differential equation (3), one finds

$$\left(j\omega L + R + \frac{j}{\omega C}\right) i = V$$

which is in the general (Ohm's Law) form

$$Z_L = V \tag{3'}$$

where

$$Z \equiv R + j\left(\omega L - \frac{1}{\omega C}\right) = |Z|\, e^{j\phi} \tag{4}$$

where

$$|Z| \equiv \sqrt{R^2 + \left(L - \frac{1}{\omega C}\right)^2} \tag{4'}$$

and

$$\varphi = \tan^{-1}\left(\frac{\omega L - \frac{1}{\omega C}}{R}\right) \quad . \tag{4''}$$

and, in order to satisfy Eq. (3'), $\theta = -\phi$.

VERSAR INC.

Several cases may be considered:

(A) $\omega L - \frac{1}{\omega C} \equiv 0$, circuit is purely resistive

then, from (4') and (4")

$$Z = R \, , \; \phi = 0 \quad .$$

(B) $\omega L \equiv 0$,

$$\phi = \tan^{-1} \left(- \frac{1}{\omega R C} \right) = - \tan \left(\frac{1}{\omega R C} \right)$$

$$Z = \sqrt{R^2 + \frac{1}{\omega^2 C^2}} \quad .$$

(C) $\omega C \equiv 0$,

$$Z = \sqrt{R^2 + \omega^2 L^2}$$

$$\phi = \tan^{-1} \left(\frac{\omega L}{R} \right) \quad .$$

The power dissipated in a series P_o, L, C circuit is given by

$$P = \frac{1}{T} \int_0^T VI \, dt$$

where T is the period $\equiv \frac{1}{f}$

which, on integration, yields

$$P = I_o V_o \cos \phi \quad (5)$$

where ϕ is the phase angle given by 4' .

The importance of the phase angle is best described by noting that electrical power is generated in such a manner that the voltage and current are in phase, i.e. $(\cos \phi)_{generation} \equiv 0$.

Hence

Power generated - power consumed = Power losses in

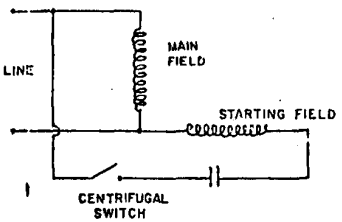
$$V_o I_o - V_o I_o \cos \theta = V_o I_o (1 - \cos \theta) = \text{power loss due to unfavorable phase angle}$$

Since the voltage is fixed and $\cos \theta < 1$, the transmission line current must be increased in order to supply the load when there is a lagging phase angle. However, the resistive losses in the transmission lines are proportional to the square of the current transmitted. Therefore, efficient transmission of electrical energy requires that the net phase angle, or power factor, of the load be as close to unity as possible. This power factor correction is achieved by the introduction of a capacitor in series with the inductive load at the load end of the line.

The use of capacitors for power factor correction is a major use of PCB filled units. Since these capacitors are normally built into electrical equipment such as fluorescent light ballasts and industrial motors, they must be non-flammable and able to operate at relatively high temperatures.

5.1.1.2 Motor Starting Circuits. Electric motors for residential use are designed to operate on single phase current. A number of different methods are used to develop the rotating magnetic field that is required to start the motor, and these methods differ in the amount of torque that is developed at low speeds. Certain applications, particularly compressors in air conditioning units, require a very high starting torque. This is achieved in a single phase motor through the use of a capacitive starting circuit.

In a capacitor motor stator windings are connected, at start, as shown below:



where the starting field is connected to the supply through a capacitor, the result is a starting winding current which leads the applied voltage. Hence, at standstill, the rotor sees fields nearly 90° apart in time as well as 90° apart in space. The resulting, effectively rotating, field results in high starting torque and a high power factor (important during the period when the back emf due to rotor motion is low so that the starting current is significantly higher than the running current). Once the rotor is up to speed, the starting winding is disconnected by the centrifugal switch.

In some applications, two capacitors are used in startup, one being removed when rotor is up to speed. The remaining capacitor helps adjust the power faster during run.

5.1.2 Construction of Industrial Capacitors

5.1.2.1 Function of the Dielectric Material

When a material medium is placed within an electric field there is a tendency for the charges associated with the constituent molecules to move in the direction of the field (the positive charges move in the direction of the applied field, the negative charges in the opposite direction). In the event that the material is a conductor, the mobile charges, usually electrons, will move freely under the influence of the field and a current is said to flow in the conductor. On the other hand, if the material is a non-conductor, the effect of the applied electric field is to cause a spatial displacement of the charge centers of the constituent molecules with the result that there will be induced surface charges on the material. The charge on opposite faces will be opposite in sign and will be so arranged as to generate an electric field within the material opposing the applied field. Such a

material is known as a dielectric and is characterized by a parameter defined as the ratio of the electric field that would exist in that space if the medium were replaced by vacuum to that actually found within the dielectric - this parameter is referred to as the dielectric constant. In general, at least at low frequencies, the dielectric constant of most materials is greater than unity.

Since the effect of an applied electric field on a dielectric medium is the generation of a surface charge, it is clear that work must be done in the separation of these charges. Clearly, the larger the applied electric field, the larger the surface charge, and conversely, when the electric field is removed, the surface charge is zero. The energy that is required to establish the necessary surface charge is then said to be stored within the dielectric and can, in most cases be recovered without loss by removing the external electric field.

In practice, the external electric field is established by applying electrical charges to a pair of metal plates placed on the opposite surfaces of the dielectric to form a device called a capacitor. The capacitance of the resulting structure is defined as the ratio of the charge on either of the conducting plates to the electric potential existing betwen the plates. Alternatively, the capacitance may be defined in terms of the energy stored within the dielectric as

$$C = \frac{2W}{V^2} \quad (1)$$

where C is the capacitance, W is the stored energy and V is the applied voltage.

Although the geometry of the conductor-dielectric sandwich can take a wide variety of forms, the specific geometry that is of most interest is that in which the conductors are parallel plates separated by the dielectric. In this case the capacitance of the device is given as

$$C = \frac{e\lambda}{d} \quad (2)$$

where e is the dielectric constant, A the area of each plate and d the spacing (the thickness of the dielectric).

As is stated above, the magnitude of the surface charges that are formed on the dielectric increases as the applied electric field increases. Eventually,

the external electric field may become sufficiently strong as to rupture the bonds that hold together the charges on the individual constituent molecules with the result that the dielectric breaks down; i.e., conducts current. The critical field strength, or rather the critical voltage, where

$$V_c = E_c d \quad (3)$$

is defined as the maximum potential gradient (voltage) that the dielectric can sustain without rupture. Clearly, the dielectric constant and the critical voltage, or dielectric strength, are essentially unrelated.

When several capacitors, say C_1 and C_2 are connected in parallel, then the voltage across each is the same, V, while the charge on the capacitors is $Q_1 = C_1 V$ and $Q_2 = C_2 V$, hence the capacitance of the parallel combination is given as $C_t = C_1 + C_2$. (4) On the other hand, if the two capacitors were connected in series, then the charge, Q, would be the same for each. In this case, the respective potentials would be given as $V_1 = Q/C_1$ and $V_2 = Q/C_2$, with the result that the total capacitance is given as

$$1/C_t = 1/C_1 + 1/C_2 \quad (5)$$

From the above considerations it can be seen that the effect of even a small hole through the dielectric will be to produce a very small reduction in the overall capacitance, since the resulting structure may be considered as two capacitors, one with the normal dielectric, the other with air dielectric, in parallel, On the other hand, the breakdown strength of air is considerably less than that of most practical dielectric materials, so that the effect of such a discontinuity in the dielectric will primarily be in reducing the critical voltage of the resulting structure.

On the other hand, the effect of a gap between the dielectric and the plates is more serious in that the resulting structure will act as if it were made up of several capacitors in series. From Eq. 5 above, it can be seen that the smallest capacitor in a series circuit will determine the total capacitance of the structure. Thus, a gap between the plates and the dielectric will have the effect of reducing the capacitance without a reduction in the dielectric strength.

In most practical devices, the assumption that the sole effect of the dielectric is the reduction of the internal electric field by the induction of surface charges is not entirely correct. In all such practical cases, there is a

leakage current that flows through the dielectric. The effect of this leakage current is the production of Joule heat within the dielectric. Useful dielectrics are such that this leakage is very small but the heating effect is not always negligible as will be discussed below.

5.1.2.2 Practical Capacitors

As pointed out above, in its simpliest form, a capacitor is a pair of metal plates separated by a suitable dielectric. Depending on the application, a great variety of structures have been used ranging from parallel plate-mica or glass dielectrics for very small capacitors, through tantalum-tantalum oxide-tantalum structures which have very large capacitances with very low operating voltage ratings. The capacitors that are of interest in this study have capacitance values in the range of a few tenths to tens of microfarads and are usually spiral wound of two thin aluminum foils and two paper spacers. To illustrate the utility of spiral winding a 0.5 mfd capacitor made of two layers of aluminum foil 2.5 inches wide by 0.0005 in thick and alternate layers of paper (dielectric constant 2) 0.001 in thick, would have a diameter of only 0.9 in; whereas, in the plane parallel configuration, the structure would be 2.5 in by 220 in. Incidently, taking the dielectric strength of the paper to be of the order of 500 kv/cm, the voltage rating of the above example capacitor would be about 1250 volts.

There are several pitfalls in the manufacture of such spiral wound metal/paper capacitors associated with the necessity of avoiding the presence of small imperfections in the paper dielectric and the necessity of insuring complete and reliable matching of the metal foils to the surfaces of the paper dielectric. As an alternative to the requirement of very high quality control of the paper and of the forming process, it has been found to be cost effective to evacuate the spaces within the wound capacitor and to subsequently fill the voids with a suitable liquid dielectric material prior to sealing the completed unit.

5.1.2.3. Required Properties of Dielectric Liquid

The properties that are essential for the liquid dielectric can be enumerated in terms of the functions that the liquid must fulfill as follows:

- Electrical Properties - Should have a dielectric constant at least as large as that of the dielectric and a dielectric strength at least as high as that of the dielectric.

- Physical Properties - Must be liquid at a suitable temperature to allow processing of the device. Further, the filler should be liquid over the operating temperature range of the resulting device with a sufficiently small expansion coefficient so as to fulfill its function over the entire temperature range. Must have a boiling point sufficiently elevated as to insure that the vapor pressure over the temperature range of the device does not cause rupture of the closure.
- Chemical Properties - Must be chemically compatible with the dielectric material and with the metal plates. Specifically the dielectric liquid must wet both the plates and the dielectric without altering either chemically or physically over the entire temperature range of the device. The material must also be chemically stable at elevated temperatures so that its properties do not change over time.
- Flammability - Should be of such a chemical structure as to be non-flammable and as to produce no flammable breakdown products in the event that electrical breakdown does occur within the device.
- Cost and Availability - Should be cheap and readily available with well defined and standarized properties.
- Toxicity - Should be non-toxic and its possible breakdown products should be non-toxic.
- Environmental Persistence - Should be environmentally degradable and non-bioaccumulating.
- Legislative Acceptability - Should be acceptable under the laws of the U.S. and of all other countries to which capacitors are exported.

5.1.3 The Use of PCBs in Capacitors

The commercial mixture of PCBs that is used in capacitors is known as Aroclor 1016. This material is the standard against which the properties of any other proposed capacitor dielectric fluid must be compared.

VERSAR INC.

5.1.3.1 Properties of PCB Capacitor Fluid

The relevant properties of Aroclor 1016 are as follows:

- Electrical Properties

dielectric constant (ASTM D-149-44)	5.85 (25°C)
diclectric strength (ASTM D-149-44)	>35 KV
Resistivity (ASTM D-257-46)	>500 x 10^9

- Physical Properties

melting point (pour point)	-19°C
boiling point	325-366°C
coefficient of thermal expansion	.00068 cc/cc/°C

- Chemical Properties

corrosiveness: liquid - noncorrosive
- breakdown products - corrosive

solvency: high, but satisfactory materials have been developed

stability (max. service temp.) 85°

- Flammability

liquid (Cleveland open cup flash point) 141°C

breakdown products (primarily HCl): nonflammable

- Cost and Availability

Cost .40/lb.

Availability - no problem

- Toxicity

liquid: short term: low
long term: carcinogenic and embryotoxic

breakdown products (from fire)
short term: toxic (HCl)

- Persistance

  environmental - very
  bioaccumulating - very

- Legislative Acceptability

  banned in Japan

5.1.3.2 Advantages and Disadvantages of PCBs in Capacitors

The only major problem arises from the extreme environmental persistence and long term carcinogenic properties of PCBs. In addition, the restrictions on the use of PCBs in electrical equipment exported to Japan will require that suitable alternatives be available.

5.1.4 Alternates to the Use of PCBs in Capacitors

As a guide to the evaluation of a candidate substitute for the PCBs in capacitor applications, there are two main approached that might be adopted: (a) a straightforward substitute that would require minimal alternation of the present production techniques; and (b) the introduction of new production techniques designed to obviate the need for a filler. In either case, the prime requirement, and indeed the basis for this exercise, would have to be that the alternative solution be significantly less environmentally distressing.

5.1.4.1 Substitutes for PCBs

To examine the first approach, it is noted that so long as the present method of construction is used, the filler is required and must necessarily satisfy requirements a, b and d at least as well as is the case for the PCBs. The only alternative to these requirements is a more or less severe restriction on the operating temperature range of the completed device and is probably not desirable. On the other hand, some sacrifice in the requirements on the range of dielectric constant and dielectric strength seems possible by increasing the dimensions of the devices. It would appear that in many applications this increased size would be troublesome but not so serious as to be impractical. Further, there are applications in which the extreme non-flammability of the filler and of its possible breakdown products could be somewhat relaxed. Finally, the cost factor could be considerably relaxed.

VERSAR INC.

A number of compounds are being developed as replacements for PCBs in capacitors. The following list of compounds must all be considered as possible substitutes for PCBs.

Mineral Oil: In standard use in capacitors until replaced by PCBs in the early 1930's. Has a lower dielectric constant than PCB-225 vs 2.85, resulting in a required 250% increase in capacitor area. The resulting capacitors will be 35% to 200% larger than the PCB capacitors. Mineral oil is flammable as are its breakdown products. Flash point is 145°C.

Castor Oil: Used in DC capacitors. Breaks down in AC field.

Dibutyl Sebacate: Unstable in contact with paper. Used in parallel plate capacitors. Should be similar to mineral oil inflammability.

Phthalate esters: Dioctyl phthalate is used in capacitors in Japan, and by one U.S. manufacturer in capacitors built for export to Japan. Limited to 85°C, vs 55°C for PCB capacitors. Di-nonyl phthalate has been developed and proposed by Exxon under the trade name of ENJ 2065. There is some concern that these compounds may be carcinogenic.

Isopropyl dichlorobiphenyl: Similar to PCB in properties. Being developed in France by Prodotec for electrical equipment manufacturers. Claimed to be less bioconcentrated than PCB (1016) and to degrade more rapidly. Present costs are higher than PCB, resulting in a 5 to 10% increase in the cost of capacitors.

Silicones: Being developed in U.S. by Dow Corning and in Japan. Promised 1976 introduction.

Butyl Monochloro diphenyl oxide: (Dow Chemical XFS-41692). All short term tests look good, but there is a possibility of conversion dioxins which are very toxic. Presently undergoing service tests by McGraw Edison. Dielectric constant equal to PCB - direct substitution possible.

Persistance is measured by degradation to CO_2 caused by digestion with sewage sludge microorganisms. The non-butylated and monobuty components of the mixture degrade 1400 and 45 times faster (respectively) than PCBs (Aroclor 1016) but the dibutyl compound degrades at only 3.5 times the PCB rate. The latter compound comprises about 20-25 percent of the mixture. Therefore the mixture is expected to degrade over three times faster in the environment than PCBs. The chemical reactivity and the photo decomposition data are not available currently.

Bioconcentration by fish was measured by the ratio of equilibrium concentrations of the fluid components in trout muscle vs ambient water. The ratio is about 800 for the most concentration component (dibutyl), about 300 for the least concentrated component (mono- and tri-butyl) but about 10,000 for 2,2',4,4' tetrachloro biphenyl (a PCB). Therefore the bioconcentration is over ten times less than PCBs.

Acute toxicity (oral administration to rats) of both DPO and PCBs is very low: greater than 10 gm/kg has been cited for DPO and greater than 1.6 gm/kg for PCBs. The toxicity (CLC 50) to fathead minnows is 15.4 mg/l for DPO and 0.76 mg/l for Aroclor 1016. A 7 hour rate inhalation study showed no effect for either PCB or DPO vapors. (The two classes of chemicals have about the same vapor pressure). Neither class showed any rabbit skin absorption. DPOs do not irritate rabbit skin or cause a chloracne reaction, whereas PCB does cause moderate rabbit skin irritation and the impurities in some PCB preparations (dioxins and furans) cause chloracne. The Dow Chemical fluid is not mutagenic in the Ames test. A 90-day rat feeding study showed that the fat accumulation, measured by the ratio of concentration in fat compared to diet concentration, is 22 times greater for PCBs (Aroclor 1016) than for the Dow Chemical fluid. The rate of disappearance (clearance) after the 90-day feeding period is much lower for Aroclor 1016 (60 days) than for Dow Chemical fluid (7 days).

Long Term Toxicity - no further results are currently available from the 90-day study. These results are necessary in order to evaluate the potential of chronic effects in people. Birth defect studies and reproductive function studies have not been conducted. Since this is a new proprietary compound, Dow Chemical is the only source of data.

Synthetic hydrocarbon oils - being developed by Monsanto as direct replacements for PCB. Dielectric constants equal or higher than that of PCB. Not fire resistant.

5.1.4.2 Elimination of Dielectric Liquids in Capacitors

In view of the complex and strongly interacting nature of the requirements on a filler material, there is considerable interest in the development of alternative production techniques. The rather advanced technology involved in the production of very thin plastic films of very high physical integrity, such as is required in many food packaging applications, has opened the way for the

production of plastic films of suitable dielectric constant and dielectric strength for capacitor applications. The parallel development of methods for the deposition of thin, carefully controlled metallic films on non-conducting surfaces, such as is widely practiced in the semiconductor industry, suggests that all of the problems that the filler is designed to obviate, could be circumvented by metallic films deposited onto suitable plastic substrates and the resulting structure spirally wound into useful capacitors. The essential problem associated with this approach, aside from the development of suitable high speed processing equipment, lies in the selection of a plastic substrate that is tractable but also stable at sufficiently high operating temperatures. An additional problem with this approach lies in the nature of the polymers that have been studied, nearly all of the suitable materials are themselves flammable and so are the probable breakdown products.

The technology for metallized polypropylene film capacitors comes from Pye TMC of England which is partially owned by Philips. Representatives of this company have approached most major U.S. manufacturers. Currently, this technology has been purchased by one U.S. manufacturer at a cost of four percent on their capacitor sales for the life of the technology usage. The failure rate of the dry film capacitors is reported to be 20 times that of PCB filled capacitors. Present efforts on dry film type capacitors are directed toward the development of a suitable capacitor design. The projected availability of this substitute is in 3-5 years time.

Aerovox reports that dry type metallized polypropylene capacitors could be used in fluorescent ballast application and that this substitute is good for industrial applications up to 370 volts. Application of these units up to 440 volts is considered a possibility. This substitute, when available, could replace 50 per cent of the industrial capacitor market. It will increase the cost of industrial capacitors by 20 per cent as compared to a comparable PCB unit but will double the cost of ballasts (two separate units will be required for purposes of start and storage.) The film used in these capacitors and metallizing equipment are manufactured in Europe and have to be imported. The use of this technology will require major redesign of the parent products, specifically when used in fluorescent lamp and room size air conditioner applications.

Metalized polyester film and metalized polycarbonate film capacitors are manufactured by G.E. for electronic applications, but are not available in sizes competitive with the PCB filled capacitors.

5.1.4.3 Elimination of Capacitors Through Use of Active Circuits

A "synthetic" capacitor for power factor correction can be constructed by use of a synchronous motor running without a mechanical load resulting in a leading current. This device is known as a "synchronous capacitor".

5.1.5 Summary - Substitutes for PCBs in Capacitors

5.1.5.1 Electrical Properties

Aroclor 1016 and its decomposition by-products are non-flammable. Therefore, its use in capacitor application greatly reduces fire and explosion hazards. This characteristic permits more economic designs of capacitors where safety codes require fireproof enclosures for capacitors containing flammable liquids.

The single most important property of a liquid to be used in a capacitor is its dielectric constant (the ratio of its ability relative to air to store electrostatic energy). The dielectric constant of capacitor-grade PCB is 5.85 while that of mineral oil is 2.25. Doubling the dielectric constant of the fluid used allows a reduction by half in the area of capacitor electrodes. As a result, significant savings can be realized in the costs of construction and installation of these units. Additionally, the dielectric constant of askarels matches closely that of the cellulose paper used in the capacitors (6.6 for cellulose and 5.85 for askarel). Because of the close match it is possible to stress askarel-impregnated paper to 400-500 volts/mil. While the stresses that can be applied to comparable paper-mineral oil capacitors are limited to 300-350 volts/mil.

PCB has good chemical stability, low vapor pressure and are considered adequate with regards to dissipation factor and dielectric strength. Its breakdown products, mainly HCl, have the advantage of being non-flammable, but are highly corrosive. This requires the use of corrosion resistant materials inside the capacitors.

VERSAR INC.

5.1.5.2 Toxicity

The major disadvantage of the PCB is its apparent toxicity. As mentioned, capacitors are closed electrical systems and in normal circumstances PCBs used in the capacitor do not reach the environment. However, during electrical failure, these capacitors can leak and are ordinarily discarded when they fail

The major disadvantage of the proposed substitutes is the lack of information. Lack of information on long term effects such as carcinogenicity plus their fate in the environment, prevent their being proposed as immediate substitutes to the PCBs. Many studies are underway to determine chronic effects but until data are available we should not act precipitiously.

5.1.5.3 Relative Merits of Substitute Capacitor Fluids as Compared to PCB

The relative merits for the various substitutes that have been proposed are summarized in Table 5.1.5.3-I.

5.1.5.4 Conclusions

PCBs have been used almost exclusively in liquid filled capacitors in the U.S. for the past 40 years. Therefore, it is very difficult to estimate the risk costs of switching to a flammable fluid. Approximately 100,000,000 capacitors containing PCBs are manufactured each year and are used almost universally in air conditioners, fluorescent lights, and television sets as well as in industrial applications. Therefore, even a small increase in the risk of fires could have substantial effects on the safety of the public.

The PCBs currently being used in capacitors have been reformulated (since 1971) to have similar use properties with minimum ecological persistance. Although these toxic properties of PCBs are fairly well documented, the environmental load from continued production of PCB capacitors will be small compared to past uses of PCBs. The alternative to the use of PCBs is to use a fluid having unknown and untested long term health hazards and to increase the risk of fire from capacitors in consumer and industrial electrical equipment.

There are a number of alternatives to PCB presently being tested. Sufficient data should be available within one of three years to determine whether the use of any of these alternative fluids will be warranted based on an analysis of combined health and fire risks.

Table 5.1.5.3-I

Relative Merits of Substitutes for PCB in Capacitors

	System Cost vs PCB	Fire Resistance	System Compatibility*	Short Term Toxicity	Long Term Toxicity and Environmental Effects	Availability
Mineral Oil	2X	Poor	Poor	Good	Good	OK
Phthalate esters	1.1X	Poor-fair	Good	Fair	Questionable	Used now in Japan
Isopropyl dichloro biphenyl	1.1X	Fair-good	Good	Fair	Questionable	On test in France
Silicones	1.2X	Fair	Good	Excel.	Excellent	To be introduced in 1976
Butylated monochloro diphenyl oxide	1.1X	Fair-good	Good	Fair	Questionable	On test in U.S.
Synthetic hydrocarbon oils	1.1X	Poor	Good	Good	Questionable	Lab tests at present
Solid plastic film	3X	Good	No	Excel.	Excellent	3 to 5 years

*Compatibility is the ability to use replacement capacitors in existing systems - as a function of physical/ dimensional constraints.

5.2 PCBs in Transformers

Polychlorinated biphenyls are used as liquid coolants in electrical transformers. PCBs have an advantage over the other major liquid transformer coolant (mineral oil) in that they are nonflammable. Gaseous coolants are also nonflammable, but gas cooled transformers have disadvantages which are considered below. Alternative liquid coolants are probably available, but to date none have been found which have all the advantages of PCBs. The following analysis includes a summary of the purposes of transformers in electrical circuits, heat generation in transformers, currently used cooling techniques, and materials being investigated as substitutes for PCBs.

5.2.1 Heat Generation in Electrical Circuits

In direct current electrical circuits, the power, P, delivered at a load consisting of a pure resistance (e.g., a light bulb) is the product of the electrical current, i, moving through the load and the voltage, v, across the load,

$$P = (v)(i)$$

But since current is proportional to voltage for a given resistance (that is,

$$v = (i)(R)$$

where R, the resistance, is the constant of proportionality), it follows that power delivered to the load resistance is the product of voltage, v, and the square of the current, i;

$$P = i^2R$$

Since the wires that carry electrical power from the site of generation (be it a battery or an electrical generator) to the load resistance 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 electric power source. However, 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).

For a given wire diameter, electrical resistance is proportional to the length of the wire. Thus, 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.

In alternating current circuits, the power dissipated in a resistance (either in the load or in the wires carrying the power to the load) is also given by $P = i^2R$. (The relation, $P = (v)(i)$, always applies to power dissipated in d.c. circuits, but in a.c. circuits the expression only applies when the voltage and current are in phase with each other, which isn't always the case, though in most practical instances involving purely resistive loads it is a fairly accurate means by which to calculate the power dissipated.)

The expression, $P = i^2R$, it not influenced by the phase relation between voltage and current and thus applies to both alternating and direct current circuits. It is apparent from this expression that the energy dissipated in a transmission wire having resistance R is proportional to the second power of the current; thus, if the current being delivered to the load were to be doubled, the energy losses in the transmission wire would be quadrupled.

Commercial electrical power is often generated many miles from where it is to be used. There are hundreds of thousands of miles of power transmission lines in this country, and it is not unusual for the electrical power generated in one place to be used hundreds of miles away, which means that a goodly amount of electrical resistance must be overcome in transmitting electrical energy to the user.

The method used to minimize energy losses in transmission lines is to reduce the current, i, and thus minimize the i^2R losses (also known as Joule heating losses) in the transmission wire. But in order to deliver maximum power to the load, the transmission voltage, v, must be increased since the power delivered is (as with d.c. circuits) effectively given by $P = (v)(i)$. Thus, if the transmitted current, i, is reduced by a factor of 2 - which reduces the Joule heating losses of the transmission line by a factor of 4 - the voltage of the transmitted power must be increased by a factor of 2.

In practice, however, the electric power which we use in our homes at 110 volts is transmitted at voltages ranging up to more than 700,000 volts - roughly 6500 times greater than common wall-socket voltage, which further means that Joule heating losses are $(6500)^2$ or more than 40 million times less than if the power were transmitted at 110 volts.

MONS 045567

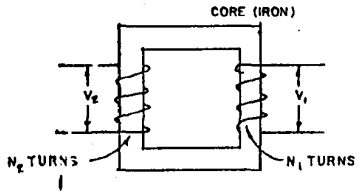
5.2.2 The Nature and Purpose of Transformers

The purpose of a transformer in an electrical circuit is to transform electrical power from its high-current low-voltage characteristics at the generating

facility to the low-current high-voltage characteristics needed for efficient transmission; and then, at or near the site of use, transformers perform the opposite transformation, bringing the power back into its low-voltage (typically 110v or 220v) high-current form.

There are two types of transformers used in the electrical power industry: power transformers (used for "stepping up" the voltage at the plant) and distribution transformers (used for "stepping down" the voltage at or near the site of power use).

Power and distribution transformers operate on the same principle - the one merely operates in a reversed fashion to the other. Using this simple



schematic diagram, the principle of operation of a transformer can be summed up by saying that the turns ration, N_1/N_2, is equal to the voltage ratio, V_1/V_2. The details of the interaction between the windings and the ferromagnetic core of the transformer need not be considered here except to say that the magnetic field produced in the core as a result of the current flowing in the windings on the input side (called the primary side) of the transformer induces a current in the output (secondary) side of the transformer. (If the transformer is being used for stepping up voltage, then the primary side is the one having fewer turns; for stepping down, the primary side is the one having most turns.)

The lengths of wire in the windings offer resistance to the flow of electricity, the result being the production of heat in the windings. Heat is also produced by currents induced in the transformer core as a result of the same mechanisms that induce currents in the secondary 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

maximized if the transformer is kept at a low operating temperature. Therefore, all transformers used in the electrical industry have provision for cooling, based on either gaseous or liquid coolant.

The coolants in common use today are:

- mineral oil
- PCBs
- air, gas } dry type

Most power transformers (i.e., step up transformers) are situated in remote locations where fire and explosions are not a threat to people or property. Mineral oils are commonly used in power transformers. Distribution transformers, on the other hand, are often located in buildings and near population areas. Such transformers must be either of the dry type or they must be cooled with non-flammable PCB-type fluids.

PCB-cooled transformers account for about 5 to 10 percent of all transformers in service. PCBs are, of course, at issue here, and certain substitutes have been suggested and are being studied. The relative merit of the currently used cooling methods and of the suggested substitutes is considered below.

5.2.3 The Properties of PCB-Cooled Transformers

Liquid coolants in transformers have better heat transfer and heat capacity characteristics than gaseous coolants. PCBs have the further advantage of being the most non-flammable of currently used transformer coolants. The other advantages of PCBs are their high dielectric strength, their outstanding chemical stability, and their low viscosity. Disadvantages, in addition to the environmental threat, are the highly corrosive HCl they produce when arcing takes place and their cost, which is about seven times as much as mineral oil, on a volume basis.

The volume of liquid coolant used in various transformers ranges from 40 to 1500 gallons (500 to 20,000 lbs, for PCBs), with an average of about 230 gallons (3000 lbs). One transformer producer, General Electric, estimates the number of PCB-filled transformers put in service in the U.S. since 1932 to be 135,000, and virtually all are still in service. Typical lifetime is often greater than 30 years, and units that do fail are usually rebuilt and returned to service. The current

production rate for PCB-filled units is about 5,000 per year, requiring some 19 million pounds of PCBs.

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

5.2.3.2 Oil-Type Transformers

PCB-containing transformers cost about 1.3 times as much as oil-filled units of the same capacity, and thus most users prefer the oil-type where possible. If safety were not a consideration, there is no reason why oil-filled transformers could not be used in all applications. Physical size would be unchanged; weight and cost would be less. However, fire underwriters do not approve of the use of oils and other flammable liquids for indoor applications; and where oil-filled transformers are not specifically prohibited as on-site replacements for PCB-filled units, the National Electrical Code imposes certain restrictions upon their mode of installation. All oil-filled transformers rated over 600 volts require vaults if the units are to be located in or near buildings; alternative fire protection arrangements are permitted for units rated less than 600 volts. Assuming space were available in existing buildings to accommodate these special auxiliary safety provisions, according to General Electric the cost of vault construction would range from $5,000 to $50,000 per transformer. Detailed cost data on vault construction is being gathered.

Oil-filled units can be installed outdoors if they are suitably isolated from flammable structures or if these structures are suitably safeguarded against fires. When transformers are located outside of the building they service, however, the low-voltage power must be brought into the building via cables or insulated buses, the cost of which could also range from $5,000 to $50,000 per installation. Also, outdoor transformers have to be rated slightly higher than indoor ones because of Joule heating losses in the cable and bus runs.

5.2.3.2 Dry-Type Transformers

Dry-type transformers cost about 1.5 times as much as oil transformers. They could be used indoors for some applications, but they have limitations that should be considered. For instance, dry-type transformers are not as efficient or reliable as comparably rated liquid-filled units. Dry units are more prone to damage due to surges and they have less overload capacity than liquid-filled units. (An Edison Electric Institute survey of failures in network transformers showed a 7 percent per year failure rate for dry units are compared to 0.2 percent for liquid-filled units. General Electric reports that many liquid-filled transformers can sustain a 100 percent overload for 2 hours, which means that liquid-filled transformers are more likely to sustain operation during periods of temporary malfunction of related equipment.)

Dry-type transformers are 10 to 30 percent larger in linear dimension than comparably rated liquid-cooled units, which puts a space constraint on their use as direct replacements for PCB-cooled units already in service. The extra noise of dry transformers - typically 5 to 10 db louder - is also a consideration for indoor installations. Outdoor installations of dry-type transformers is a problem, too, because of their sensitivity to moisture and airborne pollutants.

5.2.4 Required Properties for Transformer Oils (Heat Transfer Liquids)

A suitable substitute for PCBs in transformer applications would have all of the properties of PCBs, plus low toxicity and, especially, low environmental persistance. The properties desired of a transformer coolant are:

1. Low viscosity (for heat transfer properties); high heat capacity; high heat of vaporization
2. Non-flammability, required primarily for indoor applications
3. Chemical stability at high temperatures; low vapor pressure
4. High dielectric strength, for reliability and small size
5. Chemical and physical compatibility with other materials in the transformer
6. Inert degradation products, to assure minimum damage to other transformer parts in the event of chemical breakdown

7. High electrical resistivity
8. Low toxicity of the fluid and its decomposition products
9. Low cost

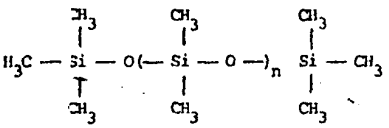
5.2.5 Substitutes for PCBs in Transformers

5.2.5.1 Fluorocarbons

Certain fluorocarbon compounds have properties similar to the PCBs, and some study is being carried out in this area. However, fluorocarbons are highly volatile in comparison to PCBs, and they are about six times as expensive at this time - though, of course, higher production volumes would lower their cost.

5.2.5.2 Silicones

Low viscosity silicone fluids (on the order of 50 centistokes) are also possible replacements for PCBs. Silicones are currently produced by four companies: General Electric, Dow-Corning, Union Carbide and Stauffer. The silicone fluid recommended by one producer is polydimethyl siloxane, which has this molecular structure:



Physical Properties

Silicone fluids have the special advantage of a relatively temperature-independent viscosity, and generally they have high flash points and low pour points. The silicone fluids have somewhat poorer heat transfer characteristics than mineral oil, but can be substituted directly for mineral oils in existing transformers.

MONS 045572

Flammability

Polydimethyl siloxane has a higher flash point than conventional, non-PCB transformer coolants: 280°C versus 146°C (PCBs have no true flash

point). The heat of combustion of 50-centistoke polydimethyl siloxane is lower than that of mineral oil - 7.67 kcal/gm versus 11.0 kcal/gm - and since the silicones burn more slowly, they are considered poor fuel.

On the Underwriters Laboratories fire-hazard classification (in which water is rated as 0 and ether as 100) polydimethyl siloxane is classified as 4 to 5, which is slightly higher than the 2 to 3 rating given to PCBs, but it is considerably less than the mineral oil rating of 10 to 20.

Ecological Persistence

These compounds do not biodegrade, measured by sewage sludge breakdown to CO_2. However, there is evidence that they partly depolymerize to low molecular weight compounds upon contact with soil and water. Since ultraviolet light decomposes methyl silicones, sunlight exposure may be the mechanism for environmental degradation.

Bioaccumulation

No tendency for bioaccumulation or bioconcentration has occurred in experiments. In mammals, the compound is not absorbed by the gastrointestinal tract or by skin.

Toxicity

The PCB substitute developed by Dow-Corning for power transformers is called DC-1090. It is a particular lot of the DC-200 series of fluids, which are polydimethyl siloxanes of various chain lengths. The literature on environmental and health characteristics of these fluids refers to at least six other fluids, most of which are probably DC-200 fluids but some of which could be other mixtures with certain additives. By necessity, the following comments are all based on the assumption that all of these compounds have identical persistance, bioaccumulation, and toxicity properties.

The acute toxicity of siloxanes is very low in guinea pigs, rats, and rabbits; 4? gm/kg/day for an extended period produces no toxic effect in guinea pigs. The LD_{50} in rats is greater than 28 gm/kg. They are not fatiguing, irritating or sensitizing to skin. FDA allows them as food additives up to a concentration of 10 ppm. In mallard ducklings and bobwhite quail, 5,000 ppm for 5

days in diet causes no effect. The human gut absorbs a negligible amount of these compounds. In 28-day oral rat studies, amounts of up to 20 gm/kg/day produced no effect, but in 90-day feeding experiments, the no-effect level was 190 mg/kg/day. In beagle dogs, 300 mg/kg/day for 120 days produced no effects. In mice 3 percent in the diet for 80 weeks produced no effects. A 2-year rat study at 3 gm/kg/days produced no effects. Adverse effects were seen in two experiments: a) a teratology study with rats and rabbits showed an excess incidence of adverse effects; b) rats injected with the fluid showed some positive pathological findings. The latter two experiments run by different investigators have produced no effects, but should be reported.

All these classes are extremely non-toxic to rodents. In fish, (e.g. fathead minnows) the siloxanes have no effect, the diphenyl oxides (DPOs) are intermediate and the PCBs are 20 times more toxic than DPOs. With respect to skin and eye sensitivity all are negative except PCBs, which produce moderate rabbit skin irratation. In subacute studies, DPO results are still pending, but indications are that it concentrates in fat tissue only 1/20 the extent of PCB accumulation, and it cleans tissue after cessation of exposure 10 times faster than PCBs. The siloxane mixtures produce no effects in feeding studies of rats, mice, beagle dogs with high exposures over 17 weeks to two years. With injection some adverse effects have been seen, but the experiment should be repeated. Siloxanes could produce birth defects but results are not clear.

The major deficiency in our knowledge of the silicones appears to be in their fate in the environment and the toxicity of their breakdown products,

Cost

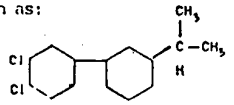
The silicone transformer fluids currently cost up to 1.5 times as much as PCBs.

Availability

Dow-Corning is currently completing evaluation of polydimethyl siloxane as a high voltage insulating fluid. They report, though, that a near term 100 percent replacement of PCBs in transformers by this fluid is not possible. If a transformer market were to develop for polydimethyl siloxane, the present domestic capacity could only be adequate to supply new transformers. The time lag for a 100 percent replacement of PCBs in transformers by polydimethyl siloxane will be on the order of 5 to 10 years.

5.2.5.3 Substituted Dichlorobiphenyl

Another possible PCB substitute is a dichlorobiphenyl with a branched hydrocarbon chain, such as:



The effect of the substitution should be to increase the biodegradability of the compound relative to PCB but to decrease its fire resistance.

5.2.6 Summary - Substitute for PCBs in Transformers

Most transformers use mineral oil as a coolant; only the 5 to 10 percent of all transformers which must have exceptional resistance to fire currently use PCBs as a coolant.

The single most important property of any liquid considered as a replacement for PCBs is its fire resistance. Other alternatives to eliminating the use of PCB transformers include the use of mineral oil transformers in vaults, the relocation of the transformer to a safe location, or the use of dry transformers. Each of these alternatives has major economic disadvantages which must be weighed against the environmental risk of continued use of PCB or the increased fire risk accompanying the use of other alternatives such as silicone liquids.

5.2.6.1 Relative Merits of Substitutes for PCBs in Transformers

The relative merits of the various alternatives that have been proposed are summarized in Table 5.2.6.1-I.

5.2.6.2 Conclusions

Economic factors totally govern the use of PCBs or their replacement by other materials in transformer applications.

PCBs are presently used where the money saved by locating the transformer in a hazardous location offsets the higher cost of PCB relative to mineral oil. The alternatives to the use of PCB include the relocation of the transformer to a safe location or the use of a fireproof vault around the transformer.

VERSAR INC.

TABLE 5.2.6.1-I

Relative Merits of Alternatives to the Use of PCB Transformer Fluids

	Toxicity	Fire Risk	Cost/ transformer	Reliability vs PCB	Convertability of Present Transformers
Mineral oil in vault	excel	excel	$5000 to $50,000	good	usually no
Relocate transformer	excel	excel	$5000 to $50,000	good	usually no
Use dry transformer	excel	excel	1.5x	poor	usually no
Silicone heat transfer oil	excel	fair/good	1.3x new $500 to 7500 per conversation	good	yes
Substituted PCB heat transfer oil	poor/fair	fair/good	?	good	yes

The substitution of any other heat transformer fluid for PCB in existing transformers will increase the risk of fires. Silicone oils are less flammable than mineral oil, and are presently being used in railroad locomotive transformers in Japan. The increased risk of fire is felt to be more than offset by the reduction in the probability of toxic spills in this application. The use of silicones, or any other flammable liquids, to replace PCBs in existing transformers in the U.S. will be a function of the probable cost of fire risk that is incurred as reflected in insurance rates and building codes.