

EXECUTIVE SUMMARY

Polychlorinated Biphenyls (PCB's) have found wide acceptance in the electrical industry in the manufacture of transformers and capacitors. Since 1972, their usage in other areas has been discontinued, so that presently these two types of electrical equipment represent the only application for these chemicals. The reasons for the elimination of PCB's are related to the toxicity and long-term persistence of various PCB isomers, if they are allowed to enter the environment. Up to now the rationale for their continued acceptance in transformers and capacitors has been that these devices represent closed systems, whereby the PCB's are effectively contained, except under unusual circumstances.

Recently it has been proposed that PCB mixtures be eliminated in electrical equipment as well. This paper explores various alternative measures which may be taken in this regard and examines the approximate costs involved for their implementation.

In the case of transformers, the complete replacement of all PCB-filled transformers would cost billions of dollars. Draining of these existing transformers and refilling them with a substitute fluid could be less costly, but would leave a small amount of residual PCB in the transformers, that would be unrecoverable. The most reasonable program would involve manufacturing all new transformers with an acceptable substitute coolant where PCB would normally be used.

In the case of capacitors, the elimination or discontinued usage of these devices could impose staggering costs on the economy. The simple replacement of PCB-filled capacitors with those using a substitute fluid could be achieved at a cost of billions of dollars. The most reasonable approach involves manufacturing all new units with an acceptable substitute fluid, and allowing the older PCB units to be retired by normal attrition over a time span of 25-30 years.

ECONOMIC IMPACT OF ALTERNATIVES TO PCB's

Polychlorinated biphenyls (PCB's) are used in the electrical industry for their dielectric and heat transfer properties. Substantial quantities of PCB's are used in the production of capacitors and transformers. A commonly used name for those PCB's which are usable in the electrical industry is askeral.

A study of the economic impact of various programs to reduce or eliminate the usage of polychlorinated biphenyls is presented in two sections: the impact on the ultimate purchaser of the transformer, and the impact on the ultimate user of capacitors.

Transformers

I. Introduction and Background

The majority of the power transformers used in the United States use mineral oils as insulating and cooling mediums. However, mineral oils have one serious drawback: they are flammable. Where transformer failures may result in fires and explosions causing threats to life and property, the use of mineral oils is greatly restricted. Fire underwriters generally will not accept the use of flammable liquids for indoor transformers, and electrical codes will not permit flammable liquid filled transformers in congested areas or buildings. As a result, non-flammable PCB filled transformers are used whenever fire protection is important or laws demand. Most PCB filled transformers are installed in or on buildings or at close proximity to buildings. Whenever fire and explosion are concerns, PCB filled transformers meet the requirements without additional containment.

Several possible substitutes exist for replacing PCB usage in transformers. There are two technically feasible alternatives to PCB's: (1) mineral

oil filled and (2) dry. A third substitute, silicone based fluids, exists, but the operating experience has been limited. Each of these substitutes has its disadvantages.

In itself, a mineral oil filled transformer is more economical than a PCB filled transformer. Oil is substantially less expensive than PCB's. Overall, the PCB filled transformer is 30% - 50% more expensive than the oil-filled unit. As a result, in many applications, mineral oil transformers are preferred. However, a mineral oil transformer cannot directly substitute for a PCB transformer, where PCB transformers are presently being used. Flammability is the primary consideration. With mineral oil transformers to meet the laws, electrical codes, and fire underwriters requirements, significant installation costs would be incurred by the user to make the transformers safe. These costs may result from the use of fireproof vaults in buildings, or, where land availability permits, outdoor substations with their attendant reconductoring requirements. The effective cost of the transformer that must be paid by the utility customer could approach twice the cost of the PCB transformer.

The dry type transformer offers comparable nonflammability of a PCB transformer. Lacking a flammable oil, it could satisfy the legal requirements. They are somewhat larger and would, therefore, require more floor space. Also, dry type units are 5-10 db. noisier. To achieve a sound level equivalent to a PCB unit of the same rating, utilities and industry must pay a price premium for a typical unit. Furthermore, dry type transformers do not have the overload capacity of a liquid (PCB or oil) filled unit. Liquid filled units would easily survive overload conditions that would cause the failure of a dry type unit. Special ventilation facilities may be required to improve dry type transformer loadability. The overall premium in price required to achieve an equivalent rating for the dry type transformer would be in the range of 10%-60%, depending on the value of the floor space, if such space is available.

An abundance of operating experience information does not exist on the silicone based fluid substitute. It is less flammable than mineral oils, but more flammable than PCB's. It is not as good a heat transfer agent as PCB. It has a larger thermal coefficient of expansion (approximately 40% greater) which could require a larger or modified transformer tank design. It is believed to be a more environmentally acceptable fluid because it has not been shown to be toxic, but it offers no improvement in biodegradability over PCB. It is more expensive than PCB's. Overall a price premium of approximately 20% above the PCB unit would be required for the silicone fluid design. If a larger or modified transformer tank were required, the price premium would increase significantly.

Bearing in mind that there are disadvantages to the substitute fluids, three alternative programs have been studied to determine their economic impact on transformer users. The first alternative assumes that no new PCB filled units will be manufactured: new transformers will use one of the substitute insulating and cooling mediums. The next program assumes that existing PCB units will be drained and filled with either mineral oil or silicone fluids and all new transformers will use one of the substitute mediums. The final alternate program assumes that all PCB filled units will be removed from service and be replaced with transformers using substitute insulating and cooling mediums.

II. Alternative Strategies

A. New Transformers Use Substitute Mediums

In 1974 approximately 3,500 PCB filled transformers, representing 5,000 MVA, were shipped by all domestic manufacturers. These units were applied in networks, power centers, substations, and as pad mounted equipment. It is estimated that 18% of these units were purchased by industrial, commercial, or medical establishments or by governmental agencies. PCB filled transformers have also found acceptance in special applications such as

rectifier stations, railway power supplies, industrial furnace facilities, and precipitator power supplies. These special application transformers have not been included in the economic impact analysis presented here.

Nearly all of these transformers were installed in, on, or near buildings so oil would not be a viable substitute for the PCB's. Major alterations to building designs would be required to house the oil units, and the cost would be prohibitive.

If silicone fluids were used the price of the transformers would be increased at least 20%, adding approximately 9 MILLION dollars to the purchase prices paid in 1974.

The dry type transformer alternative would add at least 5 MILLION dollars to the price paid for the PCB transformers in 1974.

Each of these substitute mediums would require some modifications to the building design. A conservative estimate of the cost of required minor structural changes could run as high as 9 MILLION dollars. Additional construction costs of 80 MILLION dollars or more would be accrued if substantial structural modifications are required because of the use of the substitute mediums.

B. Existing PCB Units Drained and Flushed with Substitute Medium, New Transformers Use Substitute Mediums

A second, more costly alternative, is to leave the existing askarel containing units in place, but drain the PCB material out and flush the units with some alternate fluid, then re-fill with this new alternate fluid. This has the advantage of avoiding the high cost of direct unit replacement, but it does present some trade-offs which would have to be made.

For the purpose of this analysis we have estimated that there are approximately 42,000 askarel filled transformers currently in use in the United States, exclusive of those special applications referred to in Section A above. It should also be noted that this estimate may be conservative. The Environmental Protection Agency estimates that there are 67,000 of these units in current operation.

ESTIMATED
TOTAL INDUSTRY PCB TRANSFORMER MARKET

<u>Type Application</u>	<u>Transformers in Service Units</u>	<u>GVA</u>
Network Units	4,500	5.3
Power Centers	30,500	39.2
Substations	4,100	11.9
Pad Mounts	<u>2,500</u>	<u>3.0</u>
Total	41,600	59.4

An important consideration for this alternative is that not all the PCB could be recovered from the transformer. It is estimated that a residual of about 3-10 percent would remain imbedded in the transformer insulation if normal flush-refill procedures were used. By using more sophisticated techniques such as vapor extraction and repeated trichlorobenzene washings, a 2-3 percent residual level is obtained. Additionally, while units containing PCB's can be re-filled with mineral oil, about 10 percent of the units in service may be tank space limited if silicone fluid is the replacement medium. That is, approximately 4200 units could not be flushed and refilled with silicon fluid but would have to be replaced outright. This presupposes that the flush-refill method would work with silicones.

The cost of the flush-refill method can be broken into direct labor, fluid cost and PCB disposal cost. Additionally, freight charges for the PCB disposal would appear, but this is geography dependent and is not included in the analysis.

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The cost per average unit for flushing-refilling with mineral oil is about \$2700 per unit. This includes the labor of two men for two days, the use of 400 gallons of mineral oil, and the disposal of eight drums of contaminant. The total cost for all 41,600 units would then be in the neighborhood of \$112 MILLION.

The cost for using a silicone fluid on the 90% of those units where this might be possible, would be about \$8000 per unit, based on a 20 to 1 price differential between oil and silicone. The flush-refill of 37,500 units would thus amount to about \$300 MILLION. The additional complete replacement of the remaining 10 percent of the units would be about \$194 MILLION. Thus, the total cost of this alternative, with silicone fluid, would approach \$490 MILLION.

The additional annual cost of using substitute fluids in new transformers as given in the preceeding section amounts to \$9 MILLION. These costs are relatively small compared to the overall \$490 MILLION flushing-refilling cost.

G. Replacement of Old PCB Units and New Transformer Use Substitute Mediums

If replacement of all existing units containing askarel compounds is required, the three most likely present possibilities are oil designs, dry type units, or units containing silicone fluid. Again we will use our estimate that there are approximately 41,600 askarel-containing units presently in service, with a combined capacity level of 59.4 GVA. These units are of four types: network, power center, three-phase substation and three-phase pad mounted. The largest group of these transformers is of the power center type. Taking into account the mix of units, the relative number of each, and the differences in cost per kVA of each, the replacement cost picture for the total number of units is roughly as follows:

<u>Replacement Unit</u>	<u>Total Cost</u>
OIL	\$ 1.13 BILLION
DRY	\$ 1.56 BILLION
SILICONE	\$ 1.94 BILLION

These figures are based on the assumption that the removal and installation cost would be about twice the unit cost. The total cost figure includes the purchase price of the new units.

Oil is, of course, the least expensive substitute, but may not be acceptable from a flammability standpoint. Dry type units are more expensive, and may pose other problems associated with their volume, ventilation requirements and noise levels, as discussed previously. Silicone cooled units are the most expensive alternative, and may present enough of a flammability hazard so as not to meet present fire prevention codes for the types of locations where they would have to be installed.

Not included here is the additional economic impact of using one of these three alternatives for all new units from now on. The annual cost associated with this was discussed under Section A and is relatively small when compared to the replacement costs.

III. Transformer Summary

The replacement of all existing PCB filled transformers would be an extremely expensive proposition, involving between 1.13 and 1.94 BILLIONS of dollars. Eliminating the PCB's in existing transformers already in service would cost \$490 MILLION, but there will still be 2-3 percent residual remaining within the transformer. If it is decided to ban the use of PCB fluids, the most practical approach would be to require substitute insulating and cooling mediums only in the new transformers being manufactured. Such a program would reflect a 5-9 MILLION dollar annual increase in the price of transformers using 1974 sales figures as a base.

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Capacitors

I. Introduction

(A discussion of the usefulness and elementary design of power capacitors for utility and industrial uses).

In a general sense, a power system consists of power generators, a network of lines to carry the power, and loads, or the points where the power is ultimately used. Within the network of lines are various pieces of equipment that allow the power to be distributed in the most favorable manner, taking into account such things as costs, operating constraints, safety, reliability, and other similar considerations. Because of the physical nature of the network or load equipment, two distinct kinds of power are required. The first is what is known as "real" power, measured in units of watts. This is the power that is associated with performance of work at the load site, and is the power for which most consumers actually pay. The second kind of power is referred to as "reactive" power, and generally appears as the energy required to establish and maintain electric or magnetic fields in equipment, such as transformers and motors, or in the lines themselves. Reactive power is measured in units of "vars". (The term "var" is a shortening of "Volt-Ampere-Reactive".)

In the most simple case, both of these types of power are generated at the source, transmitted around the network and distributed to the loads. A drawback to this type of system operation is that both types of power, while flowing through the system, create losses. Also, the generators and other pieces of equipment on the system must be rated to handle the duty imposed by carrying both types of power. This is very inefficient, particularly since the reactive power, while it is necessary, often does not contribute to the utility's revenues. Industrial customers are usually billed in a manner that reflects both real and reactive power usage, but reactive power generally does not appear as a part of the residential consumer's electric bill.

A favorable alternative, then, would be to "generate" this reactive power at the points where it is needed, thus reducing system losses associated with the ~~var~~ flows, and to allow the generators and various other equipment to have lower ratings, while actually supplying the same amount of useful load power. Ideally, these localized "reactive power generators" would also be very inexpensive compared to the large rotating turbine-generators that supply the real power to the loads.

Fortunately, such an ideal reactive generator does exist. It is the capacitor. A capacitor is essentially a grouping of parallel metallic sheets separated from one another by a small thickness of insulating material. By storing energy between the plates at one time and returning it to the system at another time, the capacitor successfully supplies the reactive power requirements of the system, thus freeing the generators, lines, etc., from the burden of carrying this extra load component, and also reducing the system losses. The system thus becomes much more efficient.

Since real and reactive power are "vector" quantities which do not add linearly, the degree to which the system is improved can be illustrated through the use of a "power triangle". Such a triangle is shown as Figure 1. If a right triangle is constructed with real power as the horizontal leg, and reactive power as the vertical leg, the hypotenuse represents the total power generation requirement. The ratio of the real power divided by the hypotenuse is called the "power factor" of the system. If this ratio is near unity, the required generation is only slightly larger than the real load requirements. If, on the other hand, the vertical leg of the triangle is very large, representing high reactive power requirements, the hypotenuse increases in length, and there is a large gap between the generation requirements and real load delivered. The power factor thus decreases, and the system is less efficient, since more capability is required without being able to deliver any more useful load power.

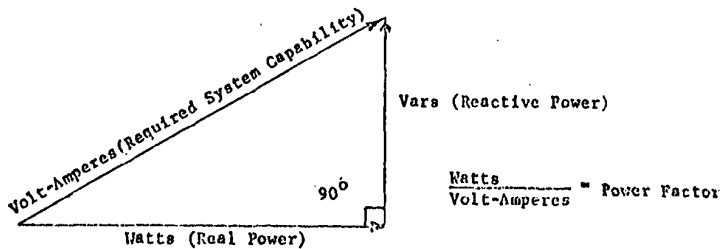


Figure 1. Power Triangle

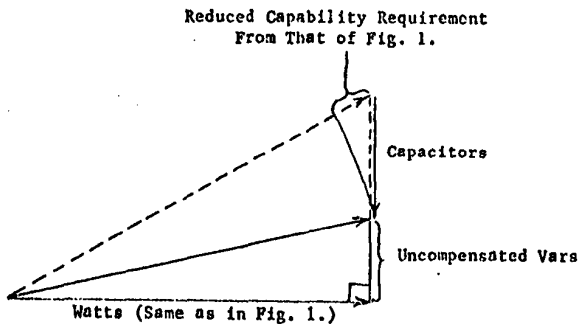


Figure 2. Power Factor Correction With Capacitors

By applying capacitors to a system, the vertical leg of the triangle can be shortened to whatever degree is shown to be economically favorable. This is shown in Figure 2. Generally, it is not economically desirable to increase the power factor to unity under all system conditions. This is because of the fact that as capacitors are added, each successive block of capacitors is somewhat less effective than the preceding block, and a point of diminishing returns is reached as one nears unity power factor. The amount of correction that seems to be in effect today will be discussed later. Suffice it to say that capacitors do an extremely effective job of shortening the reactive leg of the power triangle, and they do so in a very cost effective manner.

If capacitors are compared to other pieces of electrical equipment or plant on a dollars-per-unit-of-power basis, capacitors are clearly seen to be one of the best bargains available. For example, they are less expensive than generating plants by a factor of 200, and less expensive than combined transmission and distribution facilities by a factor of 50, on the above basis. Thus, an inexpensive unit of capacitors can be very effective in "releasing" the capacity of the much more expensive system elements for supplying useful, revenue-producing load.

The modern power capacitor in use by electric utilities and industrial customers consists of interconnected sections composed of alternating layers of conducting foil and insulation. The foil is much like ordinary food-wrapping aluminum foil. The insulation system consists of layers of high grade plastic film and draft paper usually saturated with an askarel mixture. Westinghouse uses "Aroclor 1016", one of the askarel mixtures manufactured by Monsanto. PCB's provide the best known combination of electrical properties, heat transfer properties and fire-resistant properties known to date. For this reason, virtually all power capacitors manufactured in the U.S. today contain PCB's. A more detailed discussion of the properties required of a capacitor dielectric fluid will be included under a later discussion of substitute fluids.

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II. The Present Situation

At present, approximately 270 GVAR of shunt capacitors are in service on power systems in the United States. One GVAR, or gigavar, is equal to one billion vars, or one million kilovars (kVAR). The kVAR is the most common unit of measure of reactive power, as the kilowatt (kW) is the most common unit of real power. The 270 GVAR on line represent an actual installation of about 300 GVAR over the past thirty years or so, with the assumption that about 10 percent of installed units have been retired. This will tend to give conservative and optimistic economic impact figures, if there are actually more capacitors in service than has been assumed. This figure can be readily contrasted with the approximately 400 GW (Gigawatts) of real power presently being supplied on a nationwide basis. Thus, every 4 units of real power being generated require about 3 units of reactive power, from capacitors, to keep the nationwide power system operating at a reasonably efficient level. At the present rate of load growth in this country, about 25 GVAR of new capacitors are added each year. The installed cost of these capacitors is generally on the order of \$4,00 per kVAR, which means a total annual capacitor investment of about \$100 MILLION. This is very inexpensive in comparison to the installed cost of generating plants and transmission and distribution facilities (lines and substations). The total cost per kW of combined generation, transmission and distribution is on the order of \$1000. Capacitors thus represent a very economical source of reactive power.

The present proposal to eliminate PCB's from the environment will have a direct bearing on the usage of all capacitors. Our comments apply only to power capacitor applications. The actual economic impact varies tremendously, depending on the particular alternative requirement that must be met. There are four identifiable alternatives to the present situation:

1. Total removal of capacitors
2. Existing capacitors left in place, no new capacitors added

3. Replacement of existing capacitors with those having a substitute fluid.
4. Existing units left in place, with only new additions using a substitute fluid.

These will be analyzed as reasonably as possible in the next section. The analysis treats only "shunt" capacitors, which account for the vast majority of applications. Some capacitors are installed in large "series" banks in the Western United States, to eliminate the need to install extra very long, very high voltage transmission facilities. These series banks are only economically justifiable if the lines in question are on the order of 100 miles long. Hence, their application is highly restricted, and their inclusion in the foregoing analyses would not change the economic impact figures by more than about 3-5 percent.

III. Alternative Strategies

A. Elimination of All Present PCB Capacitors, and No Installation of New Capacitors

As stated previously, about 270 GVAR of capacitors are installed on a "nationwide power system" that is generating real power at a peak level of about 400 GW. In order to analyze the economic impact of removing these capacitors entirely, a few assumptions have to be made about what amount of var compensation the 270 GVAR actually represent, and about what the system would behave like in the total absence of these capacitors. The analysis is based on the appearance of the system during the peak generation period, since this more accurately reflects the amount of system capability (generation, transmission, distribution) actually needed, than does the case of average loading conditions.

We have assumed that the 270 GVAR compensates for enough reactive power to bring the overall national system to about .94 power factor during peak conditions. Using the power triangle approach referred to in the introduction, this means that about 145 GVAR of reactive power is still being delivered

by generation facilities. The hypotenuse of this triangle, with a horizontal leg of 400 and a vertical leg of 145, is about 425 GVA (Giga Volt Amperes). This represents the actual system capability that must be available to supply the 400 GW of load power and 145 GVAR of reactive power.

We can further assume that approximately 10 percent of the real power being generated is sacrificed as system losses. Thus, the 400 GW leaving the generating plants represents about 360 GW of actual load and about 40 GW of losses. These losses appear principally as line and equipment heating.

To analyze what would happen to the system power triangle if we removed the capacitors, we must start with two basic assumptions: (1) we must supply 360 GW of actual load, and (2) system losses will increase by some factor. A good assumption is that this factor is the square of the ratio of the "uncorrected" generation requirement divided by the present, "corrected" requirement of 425 GVA.

When this new triangle is formulated, we find that the capability requirements for the uncorrected system jump from 425 GVA to 655 GVA, the real power generation jumps from 400 GW to 455 GW, and the system power factor slips from .94 to .694.

The enormous increase in capability requirements, 230 GVA, is economically staggering. This would translate to a requirement for \$230 BILLION worth of new system physical plant immediately, if present loads are to be maintained. It would, of course, be impossible to increase the total amount of system capability by 54 percent overnight, but this exercise does point out the absolute absurdity of this particular alternative.

In addition to the large increase in system capability required, there is also a large increase in system losses. The new real power figure of 455 GW represents 360 GW of load and 95 GW of losses, an increase of 137 percent over

the present loss level of 40 GW. This could translate to an additional annual cost of about \$2 BILLION because of the extra energy lost in the now less efficient system. This would be unfortunate, in light of the present increased emphasis on efficient energy usage.

Finally, the reduced power factor points to greater future costs, since each unit of new real power added in subsequent years would require 1.44 units of system capability, rather than 1.06 units with the peak power factor corrected to .94.

Clearly, then, this first alternative is no alternative at all, since it would place a catastrophic economic burden on industry, in trying to add new facilities. Since these facilities could not possibly be created in a short time, the load levels of today could not be maintained, and the resulting effect on the national economy, in terms of lost production, lost jobs, etc., would be incalculably large.

B. Existing PCB Capacitors Left in Place, No New Units Added as Load Grows

A short-haul estimate of the effect of not adding new capacitors to supply the reactive requirements of load growth can be obtained by looking at the effect over a one year time span, using projected load growth figures. As a starting point, we will assume the basic power-factor-corrected power system of Case A. This system delivered 400 GW of real power, and required 425 GVA of system capability. Projections indicate an expected increase in real power requirements from 400 GW to a new level of 435 GW in one year. If this new 35 GW of load were corrected to .94 power factor, the new system capability requirement would be 462 GVA, an increase of 37 GVA. Without this correction, the requirement would be 471 GVA, an increase of 46 GVA. Thus, in only one year, an extra 9 GVA of system capacity would be needed above the requirements for a corrected system. Projection for ten years indicates that this 9-10 GVA of additional capacity would be required in each year. This

corresponds to an extra \$9-10 BILLION investment per year, about 24 percent more than with capacitor correction. It is interesting to note that the amount of capacitors to properly correct the power factor of the new load would cost about \$100 MILLION in each of these years. Thus, these new capacitors would yield a benefit-to-cost ratio of between 90 and 100. The economic penalty for not using any more capacitors in the future is thus obvious.

C. Substitution of an Alternative, Non-PCB Fluid in Capacitors

This alternative can be subdivided into two distinct cases for analysis and comparison.

- (1) Replace Existing Capacitors with Substitute-Fluid-Filled Units, Manufacture All New Units with Substitute Fluid.

This "replacement" philosophy involves the removal of all existing units, the purchase of newer units filled with a substitute fluid, and the installation of these units at the location of prior units. It is estimated that the present purchase price of capacitors is in the neighborhood of \$2.00 per kVAR, and the installation cost is also about \$2.00 per kVAR. Present estimates seem to indicate that a substitute fluid similar to the ones that have been tried to date would result in about a twenty percent increase in unit prices. Thus, a new unit cost of \$2.40 per kVAR is assumed. The total cost for replacement of old units would be:

$$\begin{aligned}(270(10^6) \text{ kVAR}) \times (\$2.00/\text{kVAR}) &= \$540 \text{ MILLION (takedown cost)} \\+ (270(10^6) \text{ kVAR}) \times (\$2.40/\text{kVAR}) &= \$648 \text{ MILLION (new unit cost)} \\+ (270(10^6) \text{ kVAR}) \times (\$2.00/\text{kVAR}) &= \$540 \text{ MILLION (re-installation cost)} \\&= \$1.728 \text{ BILLION}\end{aligned}$$

If this program were spread over the next ten years, the amount of capacitors installed in each year would be 27 GVAR plus the capacitors required to compensate for new load. As noted before, this latter figure presently is

in the vicinity of 25 GVAR. Thus, this replacement could be effected in ten years by simply doubling capacitor output and installation. This is within reasonable bounds, and could be accomplished with a minimum of hardship. If the replacement program were to be done in five years, a tripling of production would be necessary. This would probably entail building new manufacturing plants which might be a financial burden after the five year period has expired. Thus, shortening of the program would have a cost penalty associated with it, in the form of higher unit costs. In essence, though, the replacement philosophy at least enters the realm of feasibility, compared to the previous two alternatives.

(2) Existing PCB Capacitors Left in Place, New Units Manufactured with Substitute Fluid.

This alternative is by far the most reasonable of those analyzed on an economic basis. As stated before, the use of a substitute fluid would add about 20 percent to the cost of capacitor units. It would probably have a minor, if any, effect on installation costs. Thus, the total installed cost of capacitors using a new fluid would probably only increase by 10 percent over present levels (20 percent unit cost increase, with no change in installation costs). The industry would thus spend about \$110 MILLION per year on capacitors, as opposed to the present \$100 MILLION.

With the present level of yearly installations in the 25 GVAR range, it is very easy to see that in about ten years only one half of all capacitors in the field would contain PCB's. In the 15-20 years following this first ten years, most of the old capacitors with PCB's would be expected to be retired in normal fashion. It is evident, then, that a philosophy of normal attrition spread over about thirty years would result in only a very slight effect on the budgets of the electric utility industry.

Part of the problem associated with these last two alternatives is the actual availability of an acceptable substitute fluid. A discussion of this particular problem is included in the next section.

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IV. Capacitor Dielectric Fluids

There are several factors which are important in considering any fluid as a capacitor dielectric medium. Some of the more prominent of these are as follows (not necessarily in their order of importance):

- (1) High Dielectric Constant: The dielectric constant is a measure of the relative capacity of the material for storing electrical charge. It is basically a comparison of a given thickness of the dielectric with the same measure of open dry-air space between the plates. The dielectric constant of air is thus 1.0; that of mineral oil is 2.25; that of PCB is 5.85. Thus, askarels represent a very effective dielectric medium, in that for a given amount of insulation and separation distance between the capacitor plates, a much higher value of capacitance can be obtained.
- (2) High Dielectric Strength: This is the classic measure of an insulator's ability to withstand short-time overvoltages without puncturing and failing. It must be considered in conjunction with (1), because a low dielectric strength means greater thicknesses of insulation are required, which reduces capacitance and may increase the physical size of a capacitor. Askarels are also very good from this standpoint. Insufficient dielectric strength can very rapidly decrease product reliability.
- (3) Fire Resistance: This is of obvious importance for reasons of safety, where the equipment must be installed near people or flammable buildings. Since a great many capacitors are used in industrial plants, flammability considerations of a fluid can be extremely important if fire prevention codes are to be met properly. This is perhaps one of the most significant properties of askarels. In many cases they are the only liquids which meet existing codes. None of the presently proposed substitutes is as good as PCB from a fire resistance standpoint. If one of these substitutes

were to be used, additional costs associated with such things as fireproofing of buildings, and increased fire insurance premiums, may be incurred.

- (4) Heat Transfer Capability: This can be of great significance in electrical equipment, since internal heat generation can cause severe design problems in meeting temperature rise and hot-spot criteria, if this heat cannot be adequately transferred from central parts of the unit to the outside. Askarels make excellent coolants, as witnessed by their usage in certain transformers.
- (5) Compatibility With Other Solid Insulation: The insulation system of a capacitor consists of plastic film and fluid-impregnated kraft paper. A problem in examining alternate fluids is finding out whether any long-term degradation of the insulation system will result from such things as slow chemical reactions between the elements of the system.
- (6) High Temperature Stability: It is important that the characteristics of the dielectric system remain relatively constant while at elevated temperatures for long periods of time. This is important in improving long term product reliability and reducing proneness of the device to fail or be less effective at times when it is most needed. This area has not been extensively explored with most of the proposed substitute fluids.
- (7) High Voltage Stability: This is somewhat related to high dielectric strength, but is more specifically oriented to the ability of the material to maintain its properties under long-term conditions of very high normal voltage stress. This falls under the philosophy of "working materials harder" to realize cost reductions in product designs. It

also is significant in determining how well the unit will behave in situations where normal voltages may be increased for periods of time. This area, too, has not been well explored with substitute fluids.

- (8) Environmental Compatibility: Any fluid that is used in capacitors should, ideally, be non-harmful to the environment, should it happen to escape from the sealed capacitor units due to tank puncture, leaks, etc. The fluid should be reasonably non-flammable, non-toxic to life forms, and bio-degradable, or at least inert. While PCB's are presently the best answer to the flammability problem, they have been attacked for their toxicity and persistence in the environment. All presently proposed substitutes involve a tradeoff, wherein better degradability, inertness or lowered toxicity are obtained at the cost of increased flammability.

Until about thirty years ago, mineral oil was the standard dielectric fluid in capacitors. These older designs were much larger, heavier, and costly, as well as being less safe than modern designs. The introduction of askarels heralded a new era in capacitor designs, where continuous improvement has been taking place up to the present day. The result is that present day units are very efficient, very sophisticated designs that utilize materials in nearly the best manner possible. Manufacturers have steadily reduced losses, and lowered the price per kVAR. This is why every new fluid that has been tried so far has been found wanting.

A return to oil designs would represent a gigantic step backwards in capacitor unit design. In addition to the obvious drawbacks of flammability and unit size, there is no experience in the long term stability of oil at the voltage and temperature stress levels typical of modern day designs. Even though oil is commonly used in transformers and other types of equipment, it

is not "worked" at anywhere near the levels it would be called upon to endure in capacitors, due to the small quantities of fluid involved and the confined nature of the product, where internal elements are literally squeezed to make them as small as possible.

V. Westinghouse's Efforts for Improvement

Westinghouse, as just one manufacturer, has spent hundreds of thousands of dollars over the past several years in trying to find a fluid that is better than PCB's for capacitor applications. None has been found to date. All of the recently proposed substitutes, such as butylated monochlorodiphenyl oxide fluids, or paraffin-based fluids, are basically compromise alternatives that not only do not advance the state-of-the-art in unit design, but actually represent a regression. Westinghouse is not unwilling to make such a compromise; if it is necessary, it will be done. However, we do not favor a headlong rush into mass production of less effective designs, and we will continue to look for something better.

A favorable case can be made regarding the present usage procedures associated with PCB materials. Within the past few years, Westinghouse has revised its handling procedures at the manufacturing plants using PCB's to ensure that an absolute minimum can escape into the environment. Sewer drains in PCB areas have been plugged, and PCB-contaminated material is packaged and hauled away for high temperature incineration. The very types of PCB's have been changed over this time span, so that now Westinghouse uses a PCB material that has only 1 percent of the penta- and high-chloro isomers, which are the only ones shown to be extremely persistent in the environment and which actually accumulate in animal tissues. Outside the manufacturing facility, only minute amounts of PCB can enter the environment, since the capacitor is a sealed system (welded shut) and can only discharge the fluid if the tank is punctured or the unit fails in a violent manner, causing case rupture. Most capacitor failures do not result in more than a bulging of the case, if the unit is properly protected by fuses. Thus, we feel that the environmental threat posed

by the present usage of PCB's in capacitors is negligible, and that the worth of this material in the present generation capacitor unit design is great.

V. Capacitor Summary

The capacitor has been shown to be an extremely vital component in the efficient operation of modern power systems. If a total ban on PCB's is declared, there are four possible alternative programs which can be effected. These programs and their approximate costs are:

- | | |
|---|---------------------------------------|
| A. No capacitors at all | \$230 BILLION + |
| B. No <u>new</u> capacitors, old in place | \$ 10 BILLION per annum |
| C. New dielectric fluid | |
| (1) Replacement | \$1.7 BILLION over replacement period |
| (2) Attrition of old | \$10 MILLION per annum (10% penalty) |

Attrition is the most attractive alternative, with replacement next in order of preference. Both of these alternatives require usage of substitute fluids which would likely represent steps backward in capacitor unit development, but which may be necessary as a compromise measure. Westinghouse feels that the benefits of PCB's in present capacitor manufacturing and usage modes far outweigh the rather negligible risks, and that they should continue to be used until a better, or at least equal, substitute can be found.