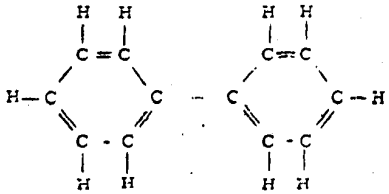
P.C.B.

Biphenyl is an aromatic hydrocarbon consisting of twelve carbon and ten hydrogen atoms. The carbon atoms are arranged in two rings of six, each joined by alternate single and double bonds, the two rings being joined by a bond from a carbon atom of one to a carbon atom of the other. Each of the remaining ten carbon atoms is bonded to a hydrogen atom. The structural formula is:



One or more hydrogen atoms may be substituted by chlorine to form a polychlorinated biphenyl or PCB. Since from one to ten chlorine atoms may be substituted, there are ten homologs possible and for each homolog of given chlorine number, several different arrangements, or isomers, of the molecule are possible. The following table shows the number of isomers theoretically possible for each homolog group, making a total of 210 isomers.

Homologs No. of Cl atoms per biphenyl molecule	0	1	2	3	4	5	6	7	8	9	10
Theoretical number of isomers	1	3	12	24	42	46	42	24	12	3	1

Commercial PCB products, of which Aroclors are examples, are produced by direct chlorination of biphenyl, the degree of chlorination being chosen to provide desired properties. As the degree of chlorination is increased the products vary from mobile liquids to more viscous and finally to waxes and solids. Lubricity, boiling point and fire resistance also increase with

increasing chlorination. In all cases, however, the products consist of mixtures of homologs and isomers; indeed, many of the desirable functional properties arise because they are mixtures. These materials are inert, chemically resistant and readily soluble in most common organic solvents. They distill in the range 275°C to 450°C and are, in the classical sense, water insoluble.

The most widely used of the series have average chlorine contents of three, five or six chlorine atoms per molecule. Because they have high dielectric strength and dielectric constant and are fire resistant, they are used to insulate capacitors and transformers. Their thermal stability leads to their use as heat transfer fluids. Good viscosity and lubricity characteristics made them useful as hydraulic fluids and lubricant, while solvent power and compatibility resulted in their selection as plasticizers and solvents for carbonless copying papers. All of these uses were reasonable because we had no evidence of significant toxicity to man or animals except in rare instances of massive prolonged exposure.

Other fluids have been substituted for PCBs for heat transfer, hydraulics, lubrication and plasticizer applications and as solvents in carbonless copying papers. However, the PCBs have a unique combination of properties which satisfy our needs as capacitor insulating fluids and for transformers where risk of fire must be minimized. No other known materials fill our needs in these areas.

Our present way of living depends for its existence on the efficient generation, transmission, distribution and use of electrical power. Transformers and capacitors are essential for the last three of these.

Because large electrical generators are rotating machines, they must operate in a gaseous environment. This limits their output to relatively low voltages, whereas efficient transmission over long distances requires high voltages. Electrical step-up transformers are required for this service, but are usually oil filled since they can be located outdoors and away from people. In some cases, to further improve the efficiency, the power is converted to direct current for transmission. This requires the use of large banks of capacitors. Near the point of use the power is converted from direct to alternating current requiring more capacitors. For local distribution, the power is stepped down to lower voltages at substations which again use oil-filled transformers since they too are outdoors. Since much of the power used is for electric motors, which are inductive, capacitors are used to raise the power factor to avoid high line loses. Distribution transformers are often located inside buildings and in crowded areas. Here fire resistance is necessary to minimize the hazard

to people. Conversion of electrical power to mechanical power for operating appliances, such as furnace blower motors, refrigerators, air conditioners, pumps for compressed air and to supply water from wells, usually involves capacitor start-run motors. Capacitors are required in fluorescent lights and high powered mercury vapor lamps for street lighting and for many other purposes.

No type of fluid other than chlorinated biphenyl with as many chlorine as hydrogen atoms mixed with trichlorobenzene or mixtures of tri- and tetrachlorobenezene gives a transformer insulating fluid which does not burn or form flamable or explosive gases when an arc is struck within it. Fluids of this type called askarels fulfill a vital safety need where transformers must be located in close proximity to people.

It is perhaps less essential that capacitor fluids be fire resistance, but still desirable since failure of a small capacitor could start a fire in a large building with many human occupants. In addition to being fire resistant, PCBs have a higher dielectric constant than other suitable fluids and permit manufacture of smaller capacitors for a given rating which have longer life. Conservation of electrical energy, by using transformers and capacitors in its distribution and use, leads to decreased pollution because of more efficient use of energy converted to electricity.

In 1966, Jensen[1] demonstrated by mass spectrometry that the unknown substances, appearing with organo chlorine insecticides during analyses of environmental speciments by gas/liquid chromatography, were PCBs. Since then, considerable analytical evidence, including much from Monsanto laboratories using increasingly sophisticated techniques (Appendix 1), has accumulated in support of the view that PCBs are widespread in nature and may reach levels which are significant in many aquatic animals and surprisingly high in some species of fish-eating birds[2-8]. The combination of chemical and physical properties necessary for accumulation through a food chain, principallly resistance to oxidation and lipid solubility, are characteristic of the chlorinated biphenyls. It is not too surprising that quite low levels in water, perhaps less than 1 part in 10^{10}, can be magnified to more than 1 part in 10^4 when passing through a food chain of aquatic species to predatory birds. The commercial PCB products like Aroclors are not single chemical species, but consist of quite large numbers of homologs and isomers[9] which although similar are not identical in chemical and physical properties. We might expect, therefore, to find variations in the extent to which these various components accumulate in wildlife and, indeed, many of the published data indicate a predominance of certain homologs, principally those containing 5 or 6 chlorine atoms, in wildlife residues[5, 6, 9, 10].

Aroclors are not particularly toxic to small mammals. Acute oral LD_{50} values for rats range from about 6 to 11 g./Kg[11]. For some marine species direct toxicity may be more serious; LC_{50} values ranging from 0-3 to 10 ppm have been reported for brown shrimp (crangon crangon)[12] and even lower concentrations have been reported to be lethal to the Gulf shrimp[13]. In the present context, where accumulation over long periods may be envisaged, the chronic toxicity of Aroclors is probably more relevant. Feeding trials over periods of two years have indicated that in small mammals (rats and dogs) significant effects are not observed at levels of 1 and 10 ppm in food. At levels of 100 ppm liver enlargement has been noted with more highly chlorinated Aroclors [14]. In birds there is evidence that breeding success may be affected by PCBs and feeding trials with Aroclors have indicated the possibility of interference with calcium metabolism leading to thin-shelled eggs and poor hatchability [4, 8, 14]. Generally, however, direct evidence that the present levels of PCBs in the environment are biologically harmful has not been established. There is reason for concern, though, that a continued accumulation of PCBs could eventually generate harmful effects in many species, particularly those near the top of a food chain of aquatic origin.

There have been suggestions that some of the PCB residues have originated from biological or photo-chemical synthesis from other substances present in the environment. It is possible, for example, that DDT can be converted to PCB by such a mechanism,[22, 23] although it seems probable that only the 4-4'-dichloro isomer would be formed in this way and this is not present in significant quantities in the environment.

The fear that unpredictable consequences might follow indefinite accumulation of PCBs in the environment has caused many ecologists to ask how this may be prevented. Some action appears to be necessary, although opinion may be divided on how drastic this action should be.

A simple solution, apparently, would be a total withdrawal of production and use of PCB products. To be effective, such a policy would need to be applied universally and experience shows that multi-laterial negotiations for introducing such measures can be long and protracted. Further, the complete withdrawal of these products would have serious consequences for some industries and the effects on the distribution of electrical power for example could produce serious problems. It is important to balance the social benefits arising from the continued use of such products against the threats posed by the environmental pollution problem. We believe that a satisfactory solution can be achieved by a combination of actions designed to limit the extent to which accumulation can occur, while retaining the use of these products in essential applications. The level reached depends on

a combination of factors including resistance to degradation, lipid solubility and rate of input into the ecosystem. The present situation has arisen because the rate of degradation of residues is lower than the corresponding rate of input. This high rate of input was due largely to the numerous applications previously discussed and which are not regarded as essential.

Degradation may occur in many ways, but the principal mechanisms affecting the environmental situation are probably biological and photo-chemical. Evidence for photo-chemical breakdown of PCBs is scanty, but U.V. photolysis of some highly chlorinated PCBs has been reported.[16] Evidence for the biodegradation of PCBs through enzyme catalysed hydroxylation is, however, substantial. Studies of biological degradation arising from exposure of single isomers and commercial mixtures to micro-organism cultures are discussed later and detailed in Appendix 2. These studies show that biodegradable PCB products are feasible and that virtually complete degradation can be achieved in selected products. Several authors report the results of feeding PCB products to various animals, coupled with tissue analyses.[5, 14, 17, 18] These show substantial metabolism of many of the PCB isomers, especially those with 2 and 3 chlorine atoms per molecule.

The use of products which contain only these less intractable isomers, by increasing the rate of degradation, should reduce the level of residues arising from a given rate of input to the environment. If the rate of input is also reduced by restricting the applications to those such as in the electrical industry, where tight control can be exercised, there is every prospect that the trend to increasing residues can be reversed and that the level of residues in the environment will fall. Monsanto has already restricted sales of products to those applications which are controllable and is supplying more degradable products where they are functionally acceptable. These actions seem appropriate to meet the situation and it is interesting to note that this is regarded as satisfactory and realistic by government representatives in the United States[19] and United Kingdom.[20]

In Sweden, where legislation to control the use of PCBs has been introduced, it is important to realize that although indescriminate use has been banned, a licensing system permits use in well controlled applications such as in electrical capacitors. Similar policies are expected to be adopted in Finland, the Netherlands and other countries.

For such a policy to be successful, cooperation between the industries involved is important to ensure that pollution arising from manufacturing processes and disposal of wastes is minimized. Some of the steps taken to ensure this are discussed in the next section.

Part of the overall policy for controlling the level of PCB in the environment is to establish a system which effectively limits the rate of entry. It has been emphasized that many of the applications for which PCB products were used formerly were, by their nature, allowing most of the product to find its way into the environment, through aqueous effluent, inadequate incineration, and generally, indiscriminate disposal methods. For many of these applications substitute products are now available. For example in plastics, resins, adhesives, carbonless papers, hydraulic and heat transfer systems and miscellaneous smaller uses, these products, although desirable, are not essential since alternatives can be used, sometimes admittedly at some penalty in cost/performance.

The actions taken to cut introduction of PCBs into the environment to a minimum are the following:

1. Monsanto, the only manufacturer in the U.S.A., decided to sell PCB-containing products only for those uses where two requirements were met:

   a) There was no technically feasible substitute

   b) The use was such that the product did not escape into the environment.

   Uses which met these requirements were as an impregnant in capacitors, as a transformer insulating and cooling fluid and a small group of high temperature heat transfer fluid applications. In all these uses, the fluid is contained in a closed system. In the case of the electrical uses, the containers are sealed and the life of the device is expected to be twenty to forty years. Larger capacitors and transformers are used by public utilities and industrial concerns who could be expected to see to it that any accidental losses from failed or obsolete units would be recovered and disposed of without environmental pollution.

   This single action cut the total use of PCBs by 50%. More importantly, it eliminated those uses which permitted the product to escape into the environment. The company has now restricted sales to electrical uses only to make certain that PCBs are not used in heat transfer systems which, if accidental leakage took place, might introduce PCBs either directly or indirectly into food products.

2. Since there is a considerable amount of experimental evidence (References) showing that the five, six and higher chlorine containing homologs degrade much more slowly than those containing less chlorine, Monsanto has altered the composition of the fluid it sells for capacitor impregnation to cut the concentration of these to a minimum. For many years, the standard fluid for capacitor impregnation had been Aroclor 1242. This fluid has, on the average, three chlorine atoms per molecule. However, as can be seen from the table below, it contains both higher and lower homologs. In particular, it contains nearly seven percent of five chlorine and higher homologs.

HOMOLOG CONTENT OF AROCLOR 1242 AND 1016

	1242	1016
Biphenyl	0.02	0.02
Monochlorobiphenyl	0.72	0.93
Dichlorobiphenyl	15.6	19.4
Trichlorobiphenyl	54.5	64.5
Tetrachlorobiphenyl	22.5	15.0
Penta and higher	6.7	0.16

Aroclor 1016, the sole fluid now sold for capacitor impregnation, in the U.S.A. contains only a few tenths of a percent of these persistent homologs. The maximum limit has been set at four tenths percent.

The amount of persistent material in fluid sold for capacitor impregnation has therefore been cut by a factor of 15 to 30.

3. Monsanto has instituted stringent procedures in its own plants to eliminate losses during manufacture and handling of PCBs. It has discontinued their use for heat transfer and hydraulic use. Effluent from the plant now contains less than 85 ppb.

4. The company has worked to educate its customers so that they will be aware of the need to prevent escape of PCBs into the environment. Several means are being used for this purpose.

   One of these has been direct consultation with each user to explain the problem. Monsanto salesmen serve as consultants to our customers on methods for reducing losses. Customers with the necessary facilities to carry them out are given Monsanto analytical procedures. Samples are analyzed in the company analytical research laboratory for those not equipped to do their own analyses. Personnel of the laboratory serve as consultants for those doing their own.

   Monsanto and the National Association of Electrical Manufacturers joined in recommending the formation of American National Standards Institute Committee C-107 to standardize proper procedures for handling PCB fluids in the electrical industry. The membership of this committee includes representatives from national groups concerned with the manufacture, use and testing of capacitors and transformers, and groups representing government and the public.

5. PCB fluids used in the electrical industry frequently become contaminated to the extent that the user cannot readily reclaim them. Formerly, these would have been discarded. Now facilities adequate to reclaim seven million pounds of material per year have been set up by Monsanto.

6. Some of the fluid is so badly contaminated, that is, it is contaminated with impurities which cannot be removed by any presently available method, that it must be destroyed. Monsanto has therefore installed an incinerator capable of burning ten million pounds of fluid per year. Waste products from this operation are free from unburned PCBs. To produce this result requires special equipment designed to expose the product to much higher temperatures for longer times than ordinary incineration equipment. The company accepts waste PCB fluid for incineration charging a fee which roughly covers the cost.

   Experiments to determine the feasibility of incinerating solid waste containing PCBs have been run. Results indicate that it would be possible. To date no such facilities have been provided.

7. For the present, it is recommended that solid waste containing PCBs be buried in sanitary land fills not adjacent to water. This recommendation is based on evidence from a long term test which shows that the rate of migration through soil is very low.

The concept that an ecologically acceptable PCB product is feasible stemmed originally from the observation that, whereas the use pattern of PCB products covered a very broad spectrum of homologs, the analytical evidence from the literature [5, 6, 9, 10] indicated that most wildlife PCB residues were concentrated in the penta/hexachloro region. This certainly implied that many of the other dominant isomers in the parent materials were not accumulating.

As part of a broad Monsanto study to elucidate the reasons for this, we have investigated the effects of micro-organisms on PCBs under aerobic conditions. Initially our studies were undertaken using activated sludge, taken from one of our biological effluent treatment plants, and pre-adapted to degrade biphenyl (Culture C_1). Although some evidence of degradation of certain single isomers and mixtures was obtained, difficulties were experienced in achieving reproducible results. We were aware that Lunt and Evans at University College, Bangor, N. Wales, had isolated from soil a pure biphenyl-degrading culture, reported to be a nocardicum of the order actinomycetes (Culture C_2). The Bangor workers had studied the breakdown mechanism for biphenyl, using this culture and had demonstrated the metabolic pathway.[21] (Details of this have been included in Appendix 2)

Using this culture for degrading single isomers of chloro-biphenyls, we were able to establish a pattern of degradation broadly agreeing with the metabolic mechanism proposed by Lunt and Evans for biphenyl. Subsequently another biphenyl degrading organism in pure culture was isolated from a canal mud (Culture C_3). This was reported as a being of the pseudonomos family. The metabolic route for degradation by this organism was shown to be different from that of the earlier culture. Subsequent studies of the degradation of chlorobiphenyl isomers showed broad agreement with this proposed metabolic pathway and it was demonstrated that most of the lower chlorine isomers of PCBs ($\leq$ penta) were susceptible to degradation by one or another of these micro-organism cultures.

When commercial mixtures of isomers were subjected to attack by these pure cultures, the analytical results indicated a different pattern of degradation than might have been predicted from the studies of single isomers. For example, the isomer 4,4'-dichlorobiphenyl was not degraded by culture C_2 although it was degraded by culture C_3 in agreement with the proposed pathways. In admixture with other isomers, as in Aroclor 1242, however, the 4-4'-dichlorobiphenyl was degraded by both cultures independently. This implied that in the presence of suitable levels of degradable isomers the organism could adapt to utilize some at least of the more intractable isomers as carbon source. Certain isomer mixtures of practical significance, such as Aroclor 1016, were prime targets of this study and the results indicated virtually complete degradation of this particular product with these two organisms. For Aroclor 1242, very substantial degradation of the significant isomers has been demonstrated and the evidence suggests that some of the more highly chlorinated penta and hexa chloro isomers

in 1242 can also be degraded through adaptation. More evidence for this is being sought in current experiments in which the more highly chlorinated components are being accentuated to establish better data, but the experiments are complicated by apparent bacteriastatic activity of highly chlorinated P.C.B.

In the work on single isomers it was established that the rates of degradation could be accelerated by including biphenyl itself with the isomer under test. The reasons for this have not been established, but one suggestion is that a mechanism of co-oxidation may be responsible [24]. Most of the work done so far has therefore included biphenyl in the study and this does raise the question whether the conditions are too artificial for extrapolation to the natural environment. For single isomers, this probably would be a valid criticism, although nature is well endowed with organic chemical structures not unlike that of biphenyl, [25] which could induce similar mechanisms for degradation.

For mixtures like Aroclor 1016, however, the adaptive mechanism which has been observed for both cultures C_2 and C_3 would probably ensure that adequate nutrient could be derived from the PCB product. Experimentation to confirm this point is currently in progress. It should be understood that degradation has clearly been demonstrated even in the absence of biphenyl: under the laboratory conditions, faster rates are observed with biphenyl present.

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APPENDIX 2

Degradation of Some Chlorinated Biphenyls by Micro-organisms

The fate of P.C.B.s in the environment is of considerable interest to ecologists. Among the various natural mechanisms for degrading organic materials, a significant contribution may be expected from micro-organisms. As part of a broad study designed to investigate causes for the apparent distribution of P.C.B.s in the environment we have studied the effects of selected micro-organism cultures on both single isomers and commercial mixtures of P.C.B.s.

The basic experimental procedure consists of shaking prepared substrates comprising P.C.B.s, mineral solutions, inocula, inhibitors, etc., for various periods of time and determining the loss of P.C.B. by G.L.C. analysis of extracts. In this work only primary degradation has been measured and we have not identified the products of the metabolic processes involved. Preliminary experiments showed that rates of degradation were increased by the addition of biphenyl; in many of the experiments, therefore, biphenyl is added initially and for experiments involving long exposures it is also added subsequently at intervals. Mercuric chloride was shown to be an effective inhibitor for the micro-organisms studied and is included at 100 ppm in a number of experiments for control purposes. Various types of shake-flask equipment have been used, but we have now standardised on an orbital incubator (Gallenkamp) operated at 130 cycles per minute controlled at a temperature of 25°C.

A standard procedure is adopted for the preparation of samples and final extraction for analysis. 5 mls. aliquots of di-ethyl ether solution containing 100 ppm P.C.B. plus 1000 ppm biphenyl (when included) are introduced into 250 ml. culture flasks (stoppered quick-fit conical flasks) and the ether evaporated by a slow stream of dry nitrogen, without external heating. To each flask is then added 100 mls. of culture solution. To maintain aerobic conditions the flasks are vented at weekly intervals and, when appropriate, biphenyl (0.005 gms) added periodically.

Analytical Methods

Samples obtained from the biodegradation experiments are much less complex than those obtained from environmental studies since they contain only the P.C.B., biphenyl, nutrients, culture and water.

For this reason the extraction of the P.C.Bs and any degradation residues from the aqueous sample is very simple but emphasis is placed upon quantitative extraction and upon the achievement of a high concentration factor.

A brief description of the extraction and analysis procedures together with a discussion of the important features is given below:

a) Extraction and Concentration

The P.C.B. sample undergoing biodegradation is in an aqueous phase and, because it has been found that in these circumstances there is a tendency for it to adsorb on the walls of the container, the complete aqueous sample is extracted with solvent (pentane) - aliquots are not used.

The pentane extract is reduced to a volume of 2 - 3 mls (a concentration factor of 50 - 100X) on a warm water bath using a nitrogen purge. Such conditions are mild enough to selectively remove the pentane without affecting the P.C.B. components. For measurements on single isomers and simple mixtures, the pentane extracts are analysed directly using a 4 ft. column, packed with 3% Silicone Oil O V 101 on 60 - 80 mesh gas Chrom Q, with a high temperature Ni^{63} electron capture detector.

For analysis of commercial mixtures, however, when the volume of 2 - 3 mls is reached a weighed amount of n decane (usually 0.1g) is added and the evaporation is continued, until all the pentane is removed. The n decane has a much higher boiling point than pentane and because of this the P.C.B. components dissolve in the n decane and are unaffected by the complete removal of pentane. This decane sample, in which the P.C.B. concentration is up to 500 x that originally in the pentane, is then used for capillary column analysis.

b) Measurement of the Degree of Biodegradation and composition of the Residues

To fully describe the results of the biodegradation of any P.C.B. sample three questions must be answered :

i) which of the original P.C.B. components have been reduced?

ii) by how much?

iii) what is the nature of the new components produced by biodegradation - if any?

The method used in all the recent biodegradation work has been that involving high resolution capillary column gas chromatography with electron capture detection. This is capable of giving accurate answers to questions (i) and (ii) and, combined with mass spectrometry is potentially capable of answering question (iii).

The decane solution of P.C.Bs obtained as described in section (a) is examined directly (using a suitable aliquot) on a stainless steel capillary column coated with Apiezon L (200', 30 thou bore) and the separated components are measured using a high temperature Ni^{63} electron capture detector. This produces a complex gas chromatogram similar to Figure 1. Under the conditions of the analysis the capillary column is capable of resolving most of the 40 - 50 components of Aroclor 1242 and the E.C. detector can measure quantitatively a component concentration equivalent to better than 1 ppb (1 in 10^{-9}).

Two features concerning this analytical procedure need further discussion.

i) Use of Apizon L as column coating

This paraffinic stationary phase was chosen early in the investigations. It is known that the material elutes components according to their boiling point and that boiling point can be related to structure. It was believed that a set of empirical rules could be drawn up to relate the structure of any P.C.B. with its elution time on Apizon L. In many cases this has turned out to be true and Simmons and Wolti (9) have published a paper showing the proposed structures of most of the components in Aroclors 1242, 1254 and 1260. Combined with our own data this has enabled us to follow the degradation of the individual components of known structure in Aroclors 1242 and 1016.

ii) Quantitative Application of the Electron Capture Detector

While the electron capture detector is ideally suited to this analysis in that it is capable of detecting exceptionally small quantities of chlorinated materials it has a potential weakness in that its response is very sensitive to molecular structure. It was expected that chlorinated biphenyls of the same chlorine content could, because of structural differences, have widely different responses. This coupled with a possible range of chlorinated biphenyls from mono to deca chloro could result in great errors of measurement of the degraded materials.

This potential weakness has not been realised in practice for the Aroclors under study (1242 and 1016) and, in fact, the capillary column chromatograms of Aroclor 1242 obtained using an electron capture detector do not differ greatly from those obtained with a flame ionisation detector (which is not seriously affected by structural differences between isomers). Reasons for this unexpected behaviour have been postulated, but the main conclusion is that for the study of the biodegradation of Aroclors 1242 and 1016 the error caused by structural differences do not affect the overall interpretation of results.

EXPERIMENTAL

Some early experiments were made using activated sludge inocula from the biological effluent treatment plant at Ruabon, N. Wales, pre-adapted to degrade biphenyl. The experimental procedures were developed during this work and some degradation of P.C.Bs was observed, but most of the results discussed here arose from experiments using specific biphenyl degrading cultures isolated by Evans and Lunt (21). Two such cultures have been investigated for the degradation of P.C.B.s. These are a nocardium of the order actinomycetes isolated from a soil sample from the Sudan (Culture C_2) and one isolated from a canal mud sample (U.K.) and reported to be of the pseudomonas family (Culture C_3). Evans and Lunt have described studies of the microbial attack by these cultures on biphenyl and have suggested the metabolic routes shown in Fig.2.

Stocks of active organisms (C_2 and C_3), received from Professor Evans, have been prepared and maintained according to his recommendations. A prepared growth media (Table 1) was inoculated with the culture and the mixture aerated continuously in the dark at a temperature of 25°C using scrubbed and filtered air. Inocula for subsequent experimental substrates were withdrawn after stopping the air flow for a brief time to allow excess biphenyl to settle. The media were prepared in 15 litre quantities. As prepared the pH was about 5.8, but was brought to 7 by addition of NaOH solution before introducing the inoculum. When only relatively small volumes of stock culture (one or two litres) were removed for experiments, the bottle was replenished by addition of an equal volume of solution containing the inorganic constituents of the growth medium. For larger quantities the practice was adopted of starting a fresh culture.

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TABLE 1 MEDIA FOR CULTURE OF BIPHENYL-DEGRADING ORGANISMS

Constituent	Grm. per litre
$(NH_4)_2\ SO_4$	1.0
KH_2PO_4	1.0
$MgSO_4 \cdot 7\ H_2O$	0.5
$Fe\ SO_4$	0.05
Biphenyl	1.0

RESULTS

A number of single isomers and simple mixtures have been studied in contact with Cultures C_2 and C_5. Packed column G.L.C., as previously described, was used to measure the loss of P.C.B. The results are summarised in Table 2.

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TABLE 2

Isomer	Culture	With or without biphenyl	Time to Degrade to 50%
2,4'-dichloro-	C_2	With	2 days
	C_2	Without	5 days
4,4'-dichloro	C_2	With	>50 days
	C_2	Without	>50 days
	C_3	With	<10 days
	C_3	Without	<15 days
2,5-dichloro	C_2	With	4 days
		Without	4 days
3,4-dichloro	C_2	With	2 days
		Without	3 days
2,5,2'-trichloro-	C_2	With	3 days
		Without	7 days
2,3',4'-trichloro-	C_2	With	<2 days
		Without	3 days
3,5',4'-trichloro-	C_2	With	6 days
		Without	6 days
2,4,6-trichloro	C_2	With	>50 days
		Without	>50 days
2,2',4,4'-tetrachloro	C_2	With	>50 days
		Without	>50 days
2,2', 4,6-tetrachloro	C_2	With	>50 days
		Without	>50 days
2',3',4',5',2,3-hexachloro*	C_2	With	<15 days
		Without	>50 days

* Mixed with 2,5,2' and 2,3',4',-trichlorobiphenyls to improve solubility.

Some commercial P.C.B. mixtures have also been studied in contact with cultures C_2 and C_3. Using high resolution capillary column G.L.C., the components have been identified by the methods developed by Sissons and Welti (9) and the percentage degradation of each component calculated from comparative peak height measurements in the chromatograms. Analyses were made after 10, 20, 30 and 60 days exposure. Biphenyl was added at intervals of 10 days. For Aroclors 1242 and 1016 exposed to culture C_2 the percentage residues for a number of components are shown graphically in Figures 3 and 4.

The concentrations of individual isomers containing 5 or more chlorines in these Aroclors are so low that it has not been found possible to quantify the extent and rate of degradation. To overcome this problem we added 10% of Aroclor 1254 to increase the more highly chlorinated homologue content. This particular mixture, however, showed no significant degradation after 25 days, the presence of the more highly chlorinated Aroclor appearing to inhibit the bacterial action.

DISCUSSION

The results of the work reported here indicate quite clearly that the lower chlorinated isomers of P.C.Bs can be degraded by enzyme hydroxylation induced by micro-organisms. The results with single isomers seems to support the work of Evans and Lunt (21) and their suggested mechanisms for biphenyl degradation with the specific organisms which they isolated. It seems reasonable to explain our findings in terms of chlorine substitution interfering with the hydroxylation steps or subsequent ring opening stages. This kind of theory would indicate that the culture C_2 would not degrade 4,4'-dichlorobiphenyl, whereas culture C_3 could. It also suggests that C_2 could degrade 2',3',4',5',2,3-hexachlorobiphenyl. These indications were supported by the experimental results obtained with single isomers and simple mixtures. The conclusion to be reached from these results, coupled with the proposed mechanisms of Evans and Lunt is that the intractable low chlorine isomers (<5Cl) of P.C.Bs would be those chlorinated in the 2,6 positions on one ring, and the 2,5,2',5' and 3,5,3',5' tetra-chlorobiphenyls. The total number of intractable low chlorine isomers would, on this basis, be 20 out of a theoretical total of 82. Of these, only 7 are likely to be present in significant quantities, based on probability considerations.

When commercial mixtures of P.C.Bs are exposed to these biphenyl-degrading cultures a somewhat different pattern of degradation appears to emerge. The most noticable feature is that many of the low chlorine isomers which appeared to be intractable when present alone, degrade comparatively readily when present in the mixture. Thus 4-4'dichloro-biphenyl degrades to 50% in approximately 2 days when exposed to culture C_2 as a component of Aroclor 1016 or Aroclor 1242.

The general conclusion from the study of these commercial mixtures is that all isomers present in significant amounts in Aroclor 1016 degrade with time constants (at 25°C) of less than 20 days; in Aroclor 1242 a small percentage, consisting of more highly chlorinated homologues may degrade more slowly, probably with some time constants exceeding 50 days.

The curves showing the pattern of degradation for some isomers in Aroclors 1016 and 1242 in figures 3 and 4 tend to fall into three groups. Those isomers containing only one or two chlorines degrade rapidly, in less than 10 days. Another group consisting mainly of trichloro-biphenyls seems to degrade rapidly, after an initial induction period, but then tends to a slower rate when the level has dropped to 10% or so. The third group, primarily tetrachloro-biphenyls, degrades more slowly, but does not show such a pronounced induction period.

This pattern of degradation can possibly be explained on the basis of adaptation and reversion. For the mono- and di-chloro-biphenyls the biphenyl-degrading cultures probably need little adaptation and will readily degrade these components. For more highly chlorinated components however, some adaptation will be necessary and the ease with which this is accomplished may depend on the concentrations of precursors available. As the precursors are degraded, however, the organisms may suffer reversion and the rate of degradation thereby decrease. As the chlorine content in the molecule is increased the rate of degradation may be expected to decrease as a result of reducing the available molecular sites for oxidation. However specific tetrachloro isomers, for which suitable precursors are available, may not need a long adaptation period and could therefore follow the type of curve indicated.

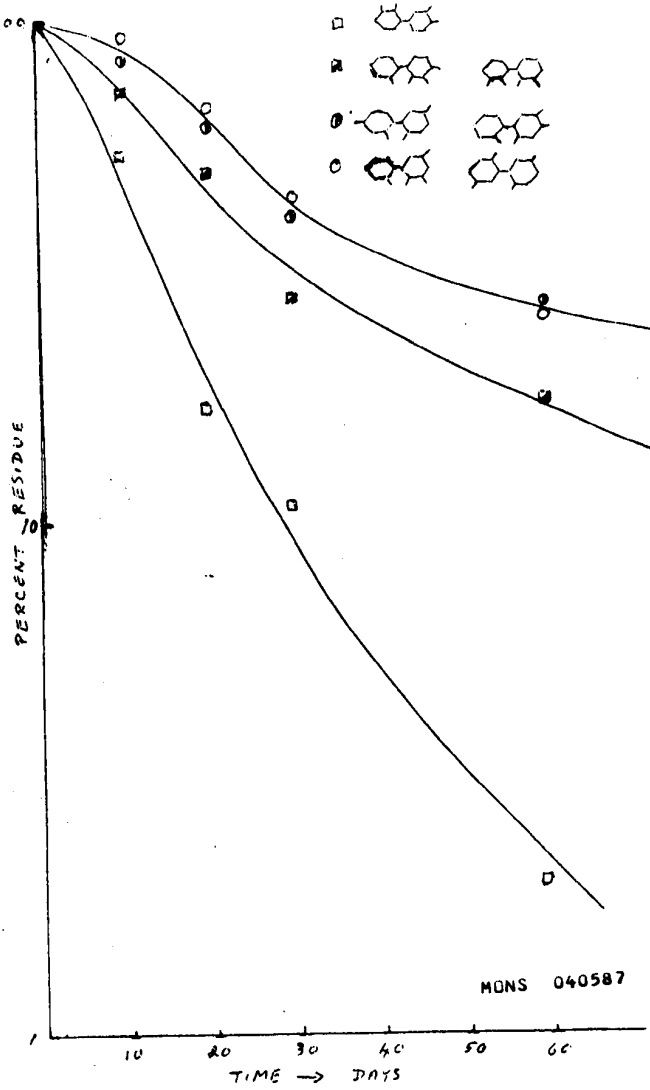

100
10
1
PERCENT RESIDUE
10
20
30
40
50
60
TIME → DAYS
MONS 040587

FIG. 4

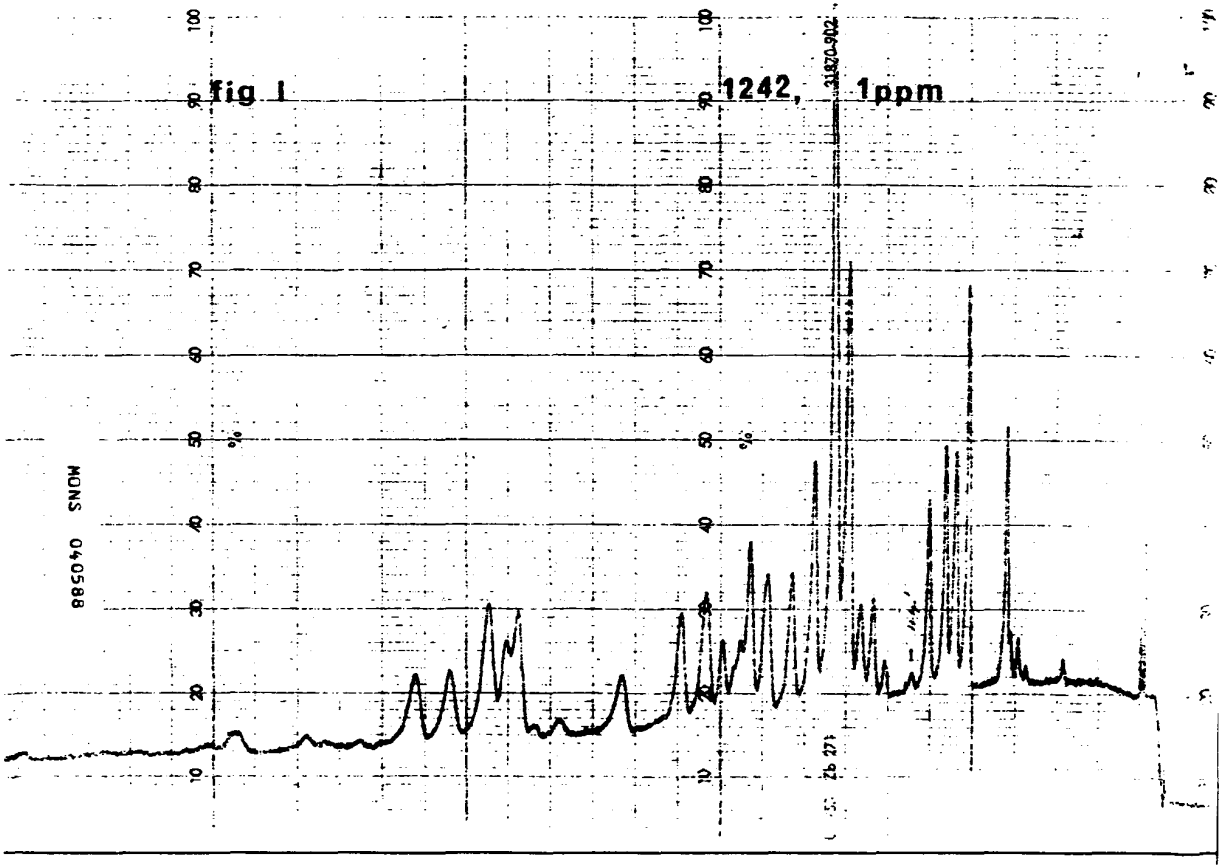
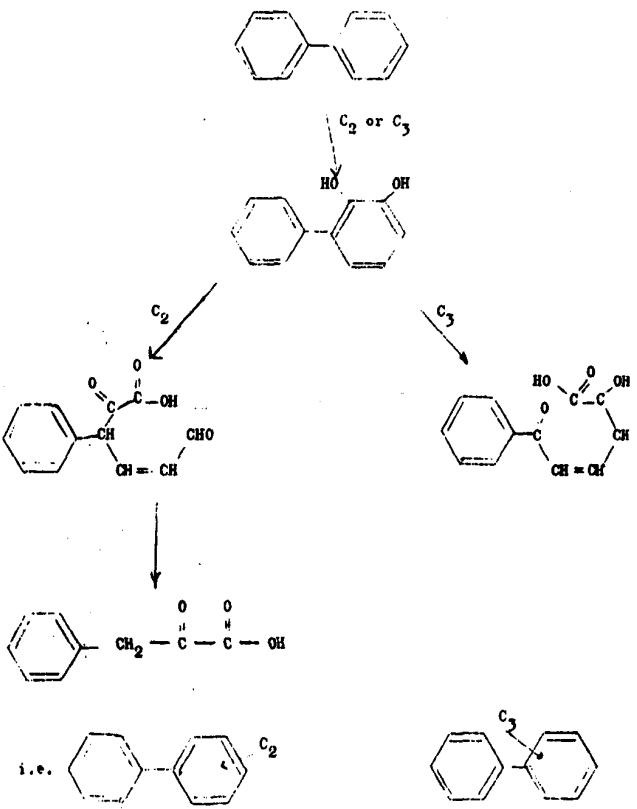


fig I
1242, 1ppm
31870-902
Zb 271
%
100
90
80
70
60
50
40
30
20
10
MONS 040588

FIG. 2 Metabolic pathways for the biodegradation of biphenyl with C_2 and C_3



MONS 040589

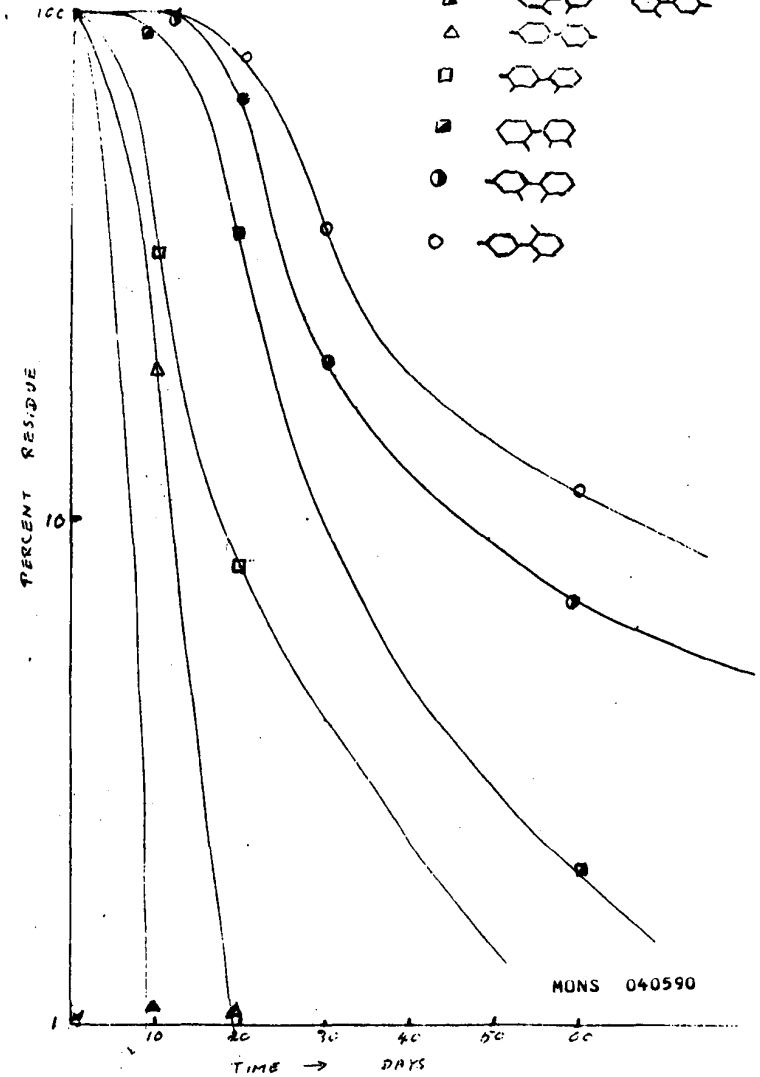

100
10
1
PERCENT RESIDUE
10
20
30
40
50
60
TIME → DAYS
MONS 040590

Fig 3