Part I Electrochemically induced reactions of some halogenated organic compounds Part II novel rearrangements of pyridazine derivatives

C. R. Sargent

Sargent, C. R. (1978) Part I Electrochemically induced reactions of some halogenated organic compounds Part II novel rearrangements of pyridazine derivatives. Doctoral thesis, Durham University.

UNIVERSITY OF DURHAM

A THESIS

entitled

PART I ELECTROCHEMICALLY INDUCED REACTIONS OF SOME HALOGENATED ORGANIC COMPOUNDS

PART II NOVEL REARRANGEMENTS OF PYRIDAZINE DERIVATIVES

Submitted by

C.R. SARGENT B.Sc. (Dunelm)

(Van Mildert College)

A candidate for the degree of Doctor of Philosophy

1978

ACKNOWLEDGEMENTS

I would like to express my thanks to Professor R.D. Chambers for considerable advice, discussion and encouragement and to Dr. F.G. Drakesmith for his help with the electrochemistry.

Thanks are also due to Dr. R.S. Matthews for his expert advice with n.m.r. data and to many technical staff for their assistance.

Finally, thanks to the S.R.C. and the Electricity Council for the provision of a C.A.S.E. Award.

MEMORANDUM

The work described in this thesis is original except where specifically stated to the contrary. It has not previously been submitted either wholly, or in part, for a degree at this or any other university.

ABSTRACT

PART I

The reduction of pentafluoropyridine gave, as the major products, octafluoro-4,4'-bipyridyl in aprotic systems and 4-H-tetrafluoropyridine with added proton donor. Carbanionic intermediates were not trapped by carbon dioxide to give acids. Voltammetric results for a series of polyfluoropyridines suggest that the negative charge in the radical anion is mainly in the 4-position.

Reduction of pentachloropyridine in dimethylformamide gave 4-H-tetrachloropyridine, with some 4,4'-bistetrachloropyridylmercury when using a mercury cathode. Intermediate carbanions were trapped by carbon dioxide, giving an acid mixture, which yielded 4-H-tetrachloropyridine and heptachlorobipyridyl on decarboxylation. Hexachlorobenzene behaved similarly.

Simple perfluoro-olefins eliminated fluoride ion on reduction and were subsequently oligomerised by it. Intermediate carbanions were trapped by water. The electrochemical products were high-boiling oils, resulting from reaction with the solvent.

Oxidation of polyfluoroanisoles containing para hydrogen gave coupling to the corresponding 4,4'-dimethoxybiphenyl derivative. No coupling occurred when this position was blocked by fluorine. Trapping of intermediate radical cations with acetic acid was unproductive.

PART II

The photochemical and thermal rearrangements of a number of perfluoroalkylpyridazines in static systems was investigated.

As had previously been reported, photolysis of perfluoro-4,5-dialkylpyridazines gave mainly perfluoro-2,5-dialkylpyrazines, although in some cases perfluoro-2,6-dialkylpyrazines were also formed.

The pyrolysis of perfluoro-4,5-dialkylpyridazines gave mainly perfluoro-4,5-dialkylpyrimidines and in some cases a small amount of the -2,5-pyrazine. Perfluoro-4-alkylpyridazines gave mixtures of perfluoro-4-alkyl- and -5-alkylpyrimidines. These results can be explained by a mechanism involving diazabenzvalene intermediates.

The photolysis and pyrolysis of mixtures gave no exchange of substituent groups indicative of a bimolecular process. In the pyrolyses, the conversion of the less reactive pyridazine was catalysed and that of the more reactive pyridazine inhibited. The relative amounts rearranged ruled out a 1 : 1 intermediate and a Diels-Alder mechanism, which would involve exchange of nitrogen, was further ruled out by ^{15}N-labelling. The catalytic mechanism proposed involves a transfer of vibrational excitation.

CONTENTS

PART I ELECTROCHEMICALLY INDUCED REACTIONS OF SOME HALOGENATED ORGANIC COMPOUNDS

CHAPTER I ELECTROCHEMICAL METHODS

CHAPTER II ELECTROCHEMICAL REACTIONS OF ORGANIC HALIDES

CHAPTER III ELECTROCHEMICAL REDUCTION OF SOME POLYHALOGENATED PYRIDINE DERIVATIVES

CHAPTER IV ELECTROCHEMICAL REDUCTION OF PERFLUORO-OLEFINS

CHAPTER V ELECTROCHEMICAL OXIDATION OF POLYFLUOROANISOLES

CHAPTER VI EXPERIMENTAL FOR CHAPTER III

CHAPTER VII EXPERIMENTAL FOR CHAPTER IV

CHAPTER VIII EXPERIMENTAL FOR CHAPTER V

PART II

CHAPTER IX NOVEL REARRANGEMENTS OF PYRIDAZINE DERIVATIVES

CHAPTER X EXPERIMENTAL FOR CHAPTER IX

APPENDICES

PART I

ELECTROCHEMICALLY INDUCED REACTIONS OF SOME HALOGENATED ORGANIC COMPOUNDS

INTRODUCTION

CHAPTER I

ELECTROCHEMICAL METHODS

I.A INTRODUCTION

An extensive literature is available on the subject of organic electrochemistry,[1,2,3] and this chapter provides only a brief introduction to the methods available to the organic chemist.

I.B A MODEL ELECTROCHEMICAL REACTION

Let us first consider the electrochemical reduction of a substrate S^+ to a desired product P,by the scheme:

$$S^+ + e^- \rightleftharpoons S^{\bullet}$$

$$2S^{\bullet} \longrightarrow P$$

$$S^{\bullet} + e^- \rightleftharpoons S^-$$

$$S^- + H^+ \longrightarrow SH$$

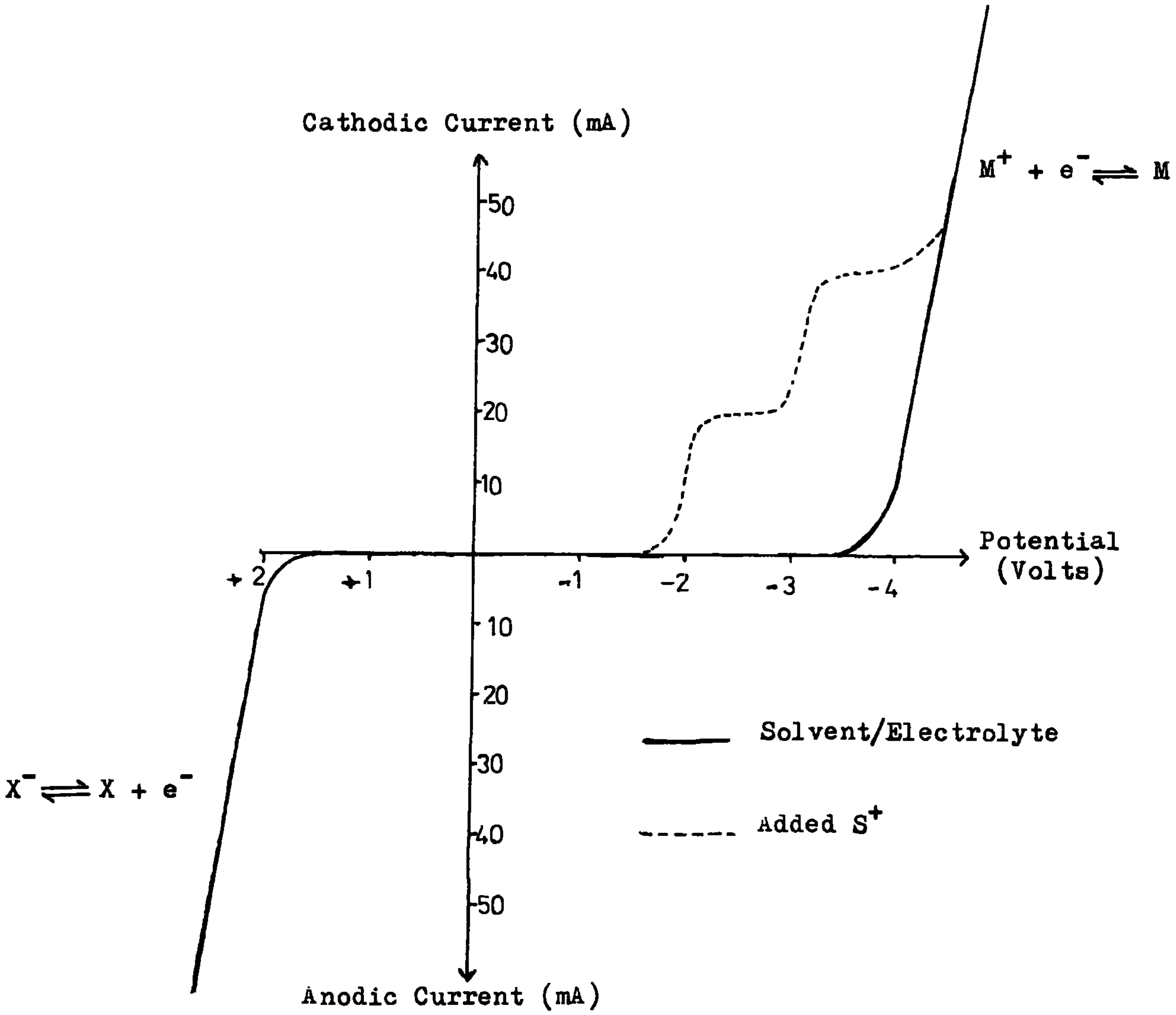
The electrolysis is carried out in a suitable solvent, containing an excess of a salt M^+X^-. This is known as the supporting electrolyte. Two inert electrodes are immersed in the solution, to serve as the anode and cathode. The reaction of interest takes place at the cathode, which serves as a source of electrons; and this is termed the working electrode. The other electrode,(in this case the anode), is called the auxiliary or counter electrode.

1. The Current-Potential Curve

The most common record of electrochemical behaviour is the current-potential curve, or voltammogram. This is a record of how the current through the electrochemical cell varies, as the potential of the working electrode is varied, relative to some arbitrary reference.(Figure 1). By convention, cathodic,(negative), potentials are plotted to the right, and anodic to the left. Cathodic currents are similarly considered positive, and plotted upwards.

In the absence of S^+ the cathodic current increases rapidly at -4.0V,

Figure 1 Voltammogram of a model reaction.



the potential at which M^+ is discharged. A similar increase in anodic current occurs at +2.0V, when X^- is discharged. These are referred to as the limiting anodic and cathodic potentials. Sometimes the limiting factor is the potential at which the solvent itself is electroactive.

In the presence of added substrate, this diffuses to the cathode, and two reduction waves of similar size can be seen. These correspond to the two one-electron transfer processes in the scheme:

$$S^+ + e^- \rightleftharpoons S^\bullet$$

and $$S^\bullet + e^- \rightleftharpoons S^-$$

Clearly, the second step is undesirable,if the aim is the production of P.

2. Controlled-Potential Electrolysis

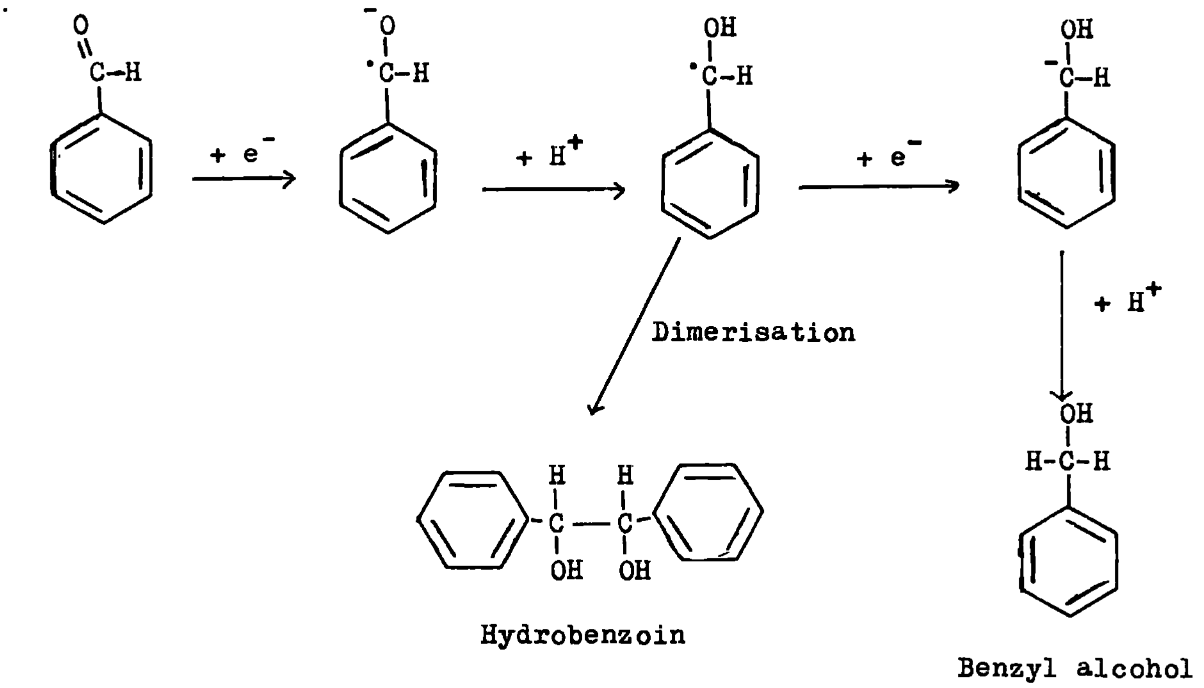
In this technique, the potential between the working electrode and a third electrode of constant potential,(reference electrode), is held at a selected value by an instrument called a potentiostat. Thus, the potential of the working electrode could be maintained at -2.5V to discriminate against the second electron transfer. The potential of the auxiliary electrode shifts to whatever value is necessary to support the same current as the working electrode. This current is provided by the discharge of X^-. With a highly resistive solution, the output voltage of the potentiostat must be very high, creating design problems.

3. Constant Current Electrolysis

Because of its greater experimental simplicity, many syntheses have been performed using a constant applied current. This poses difficulties, however. If a constant current of 10mA is maintained, this initially results in only the first stage of the reaction taking place, as desired. As the reaction proceeds, and the concentration of S^+ decreases, there comes a time when the reduction to $S^\bullet$ alone cannot support a current of 10mA. The reduction of $S^\bullet$ to S^- will then commence. This can be counteracted by having a high initial concentration of S^+, and stopping the reaction well before completion.

Another problem is that the cathode potential attained is normally near the foot of the curve. This does not matter in this example, but in some cases two electrons are transferred in one reduction wave, and on the lower portion of the curve a one-electron intermediate is produced. For example, the reduction of benzaldehyde to benzyl alcohol can also give hydrobenzoin, by dimerisation of the intermediate radical formed at the foot of the curve.[4]

Reduction of benzaldehyde:



4. Constant Voltage Electrolysis

Because of experimental simplicity, this method has also been widely used. It is possible to select a voltage across the cell, such that the cathode is at approximately -2.5V, and the reaction is selective. However, the voltage across the cell is reduced by the iR drop, caused by the cell resistance, iR_{cell} , so that:

$$E_{effective} = V_{applied} - iR_{cell}$$

Thus, as the reaction proceeds, and the current falls, the effective voltage across the cell will increase, and the second reduction may commence.

I.C SIGNIFICANT FACTORS IN ELECTROCHEMICAL SYNTHESIS

1. Solvent-Supporting Electrolyte System

The influence of the solvent and supporting electrolyte on the course of the reaction can be profound. Most processes proceed through reactive intermediates, and it is, therefore, not surprising that different products may be obtained using an inert aprotic solvent, than are

Table 1 Limiting potentials on Pt electrodes (v. S.C.E.)[5]

Solvent	Electrolyte	Anodic Limit	Cathodic Limit
Acetic acid	NaOAc	+2.0V	-1.0V
Acetone	$(n\text{-}Bu)_4NClO_4$	+1.6V	-1.0V
Acetonitrile	$LiClO_4$	+2.5V	-3.0V
Acetonitrile	Et_4NBF_4	+3.2V	-1.8V
N,N-Dimethylformamide (D.M.F.)	$(n\text{-}Bu)_4NBF_4$	+1.6V	-2.8V
Dimethylsulphoxide (D.M.S.O.)	$LiClO_4$	+1.3V	-3.4V
Hexamethylphosphoramide (H.M.P.)	$LiClO_4$	+1.0V	-3.3V
Methanol	$LiClO_4$	+1.3V	-1.0V
Methylene chloride	$(n\text{-}Bu)_4NClO_4$	+1.8V	-1.7V
Sulpholane	Et_4NClO_4	+3.0V	-2.2V
Tetrahydrofuran (T.H.F.)	$LiClO_4$	+1.6V	-3.2V

obtained in aqueous solution. In addition, organic solvents often allow the use of a wider range of potentials, and increase the solubility of organic substrates.

Most organic solvents have low dielectric constants, normally limiting the choice of supporting electrolyte to tetraalkylammonium salts, and sodium or lithium perchlorate.

The anodic and cathodic limiting potentials of some solvent-electrolyte systems are given in Table 1.

2. Electrode Material

The most generally used anode material is platinum, because of its inertness in most electrochemical environments, and its high oxygen overpotential in aqueous media. Graphite and lead dioxide are also often applicable.

A wider choice is available for cathode material, as most metals do not corrode under cathodic conditions. For preparative work, lead,mercury, tin platinum, nickel, cadmium, copper, or zinc, are normally used. Mercury has the advantage of being a liquid, enabling it to be stirred, so that a clean electrode surface is presented to the solution at all times.

In some cases different reactions may occur on changing the electrode material, and the cathode may be consumed by the formation of organometallic compounds. Adsorption of the substrate onto the metal surface may be an important factor in some reactions.

The saturated calomel electrode,(S.C.E.), is the most widely used reference electrode. It consists of a mercury electrode in contact with a solution saturated with both Hg_2Cl_2 and KCl. The half-cell reaction is:

$$Hg_2Cl_2 + 2e^- \rightleftharpoons 2Hg + 2Cl^-$$

The potential is +0.242V relative to the normal hydrogen electrode at 25°C.

3. Cell Design

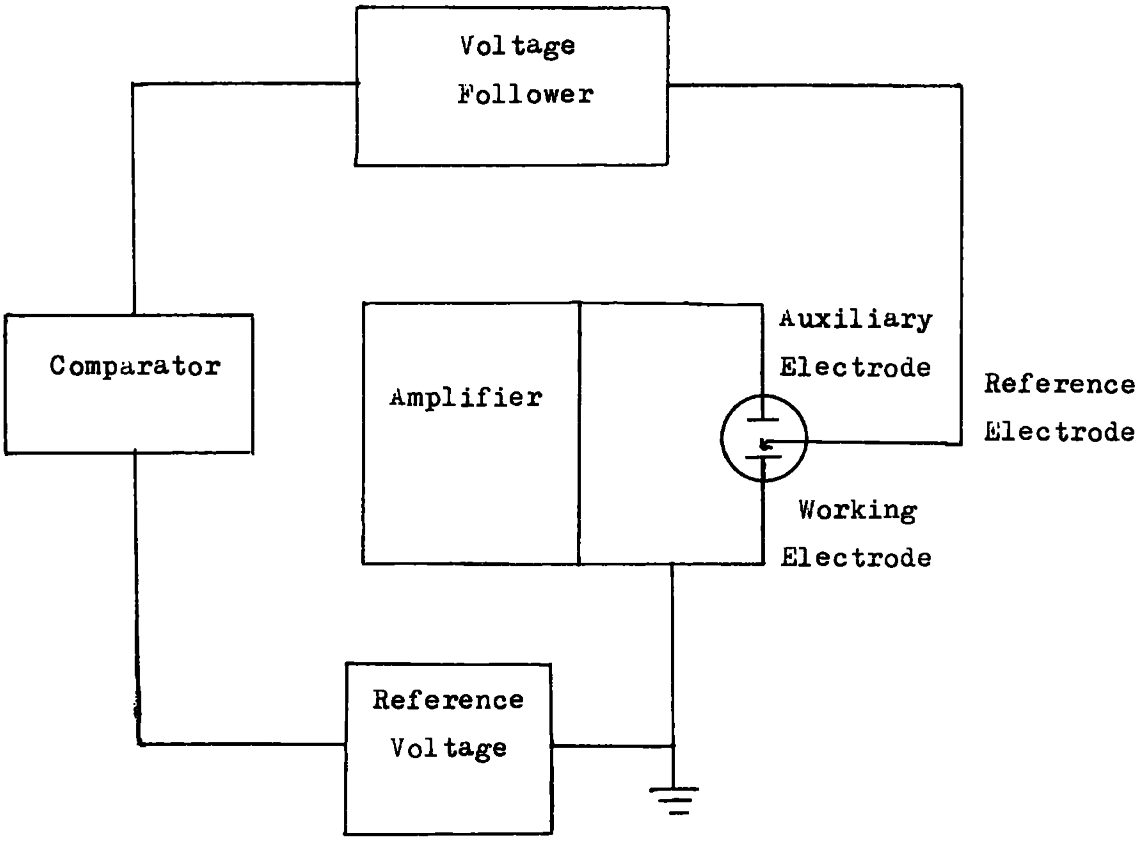
Many varying sizes and shapes of electrochemical cell have been used. There are basically two types: those consisting of one vessel; and those divided into anode and cathode compartments by some kind of semi-permeable membrane. This membrane will ideally allow only the electrolyte, and not the substrate, to diffuse through it, so that species generated at the working electrode cannot react at the auxiliary electrode to give undesired products. This is obviously the preferable arrangement, especially when a potentiostat is being used, as the auxiliary electrode can then reach very high anodic or cathodic potentials.

The use of a cell divider increases the cell resistance, as does the use of non-aqueous solvents, so to maintain a high current flow, at reasonably low cell voltages, the electrodes must be as close together as possible, and preferably parallel. The ratio of their surface area to the cell volume should be as large as possible.

Other requirements are: a salt bridge running from close to the working electrode surface to the reference electrode; and provision for stirring, cooling if necessary, and deoxygenating the solvent by bubbling nitrogen.

4. The Potentiostat

Figure 2 Block diagram of a potentiostatic circuit.



The potential difference between the working electrode and the reference electrode is continuously compared with the preset reference voltage. Any error is detected and amplified electronically, and current is passed through the cell in such a way as to minimise the error.

5. Current Efficiency

In addition to the conventional chemical yield, in electrochemical reactions the current efficiency is important. To calculate this, the amount of charge consumed during the reaction must be measured. This is done by a current integrating device, or simply by plotting a graph of current against time. The area under the graph gives the charge, in amp-hours, which is converted into faradays by the relationship:

1 faraday = 96,500 coulombs = 26.806 amp-hours

From Faraday's laws, in a one-electron process, one mole of substrate requires one faraday of electricity. The current efficiency is the number of faradays theoretically required, divided by the number actually used, normally expressed as a percentage.

i.e. $$\text{Current Efficiency} = n \times \frac{\text{no. of moles of product}}{\text{no. of faradays used}} \times 100\%$$

where n is the number of electrons required per molecule of product

The current efficiency is normally less than the chemical yield, since there may be electrochemical side reactions, which do not involve the starting material.

I.D ELECTROANALYTICAL TECHNIQUES

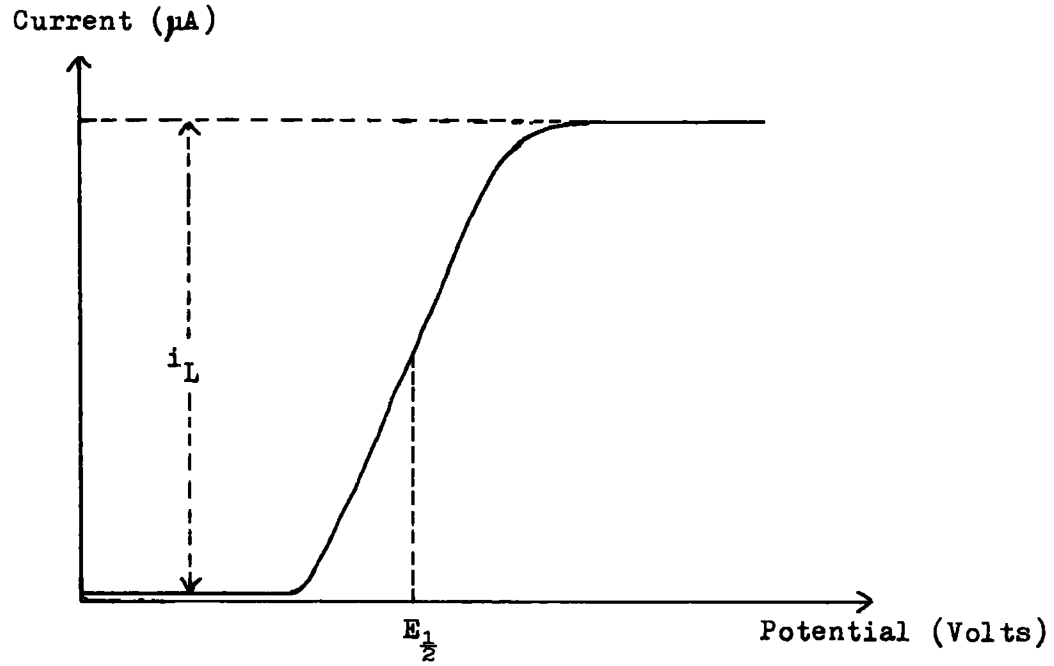
A variety of electroanalytical techniques can be used to investigate the electrode processes taking place during an electrochemical reaction. Perhaps the most popular are polarography and cyclic voltammetry. These are normally performed on dilute solutions, in the region of 1-10mM.

1. Polarography

Polarography is the term applied to voltammetry performed at a dropping mercury electrode,(D.M.E.). This consists of a capillary connected to a mercury reservoir, so that the rate of mercury flow can be regulated by adjusting the height of the reservoir. A fresh electrode surface is generated as each new mercury drop forms. As a consequence of this increase in size and subsequent disappearance of the drops, the voltammogram obtained by varying the potential linearly with time, has oscillations superimposed. These can be electronically smoothed out to give the S-shaped polarographic wave shown in Figure 3.

Two quantities, the half-wave potential ($E_{\frac{1}{2}}$), and the limiting current (i_L); are of theoretical importance. The half-wave potential is the potential at which the current is half of the limiting value.

Figure 3 Polarogram of the reversible reaction: $O + ne^- \rightleftharpoons R'$



(a) Reversible Reaction

A reaction shows electrochemical reversibility when both the oxidised and reduced forms are stable, so that the reaction can be carried out in either direction; and the electron transfer process is fast, so that the Nernst equation is valid at all times.

Nernst equation: $E = E^o - \frac{RT}{nF}\ln\frac{[R']}{[O]}$

[R'] and [O] are the activities of the reduced and oxidised forms, respectively.

Under these conditions $E_{\frac{1}{2}}$ can be related to E^o, the standard electrode potential of the reaction, and hence to the Gibb's free energy. Thus, the $E_{\frac{1}{2}}$ of a reversible process has thermodynamic significance.

Linear relationships can be found for related series of compounds, between anodic and cathodic $E_{\frac{1}{2}}$'s and the ionisation potentials or electron affinities determined in the gas phase.[6] Similar relationships exist with the theoretically calculated energies of the highest occupied orbital, (for anodic processes), or lowest unoccupied orbital,(for cathodic processes).[6, 7]

The limiting current can be used to derive a value of n,(the number electrons per molecule involved in the wave).

(b) Irreversible Reaction

A process is electrochemically irreversible if either O or R' are unstable, or the rate of charge transfer is slow. The significance of $E_{\frac{1}{2}}$ is difficult to assess, as its value depends on both the thermodynamics and the kinetics of the reaction. A common assumption made,is that for a homologous series of compounds, the $E_{\frac{1}{2}}$'s reflect changes in the kinetics. Thus, the compound which reduces at the more negative potential has been considered to have a higher energy transition state.

2. Cyclic Voltammetry

In cyclic voltammetry the potential of the electrode , in an unstirred solution, is varied linearly with time, as in polarography. This gives rise to a peaked voltammogram, as the substrate becomes depleted in the region of the electrode. The direction of the sweep is then reversed at a point past the peak, and the potential returned to its initial value, normally at the same sweep rate.

(a) Reversible Reaction

The shape of the cyclic voltammogram of a reversible reduction is shown overleaf (Figure 4). On the forward sweep, reduction of O to R' is seen, and this is reoxidised on reversing the sweep. For a reversible process, it has been shown that[8]:

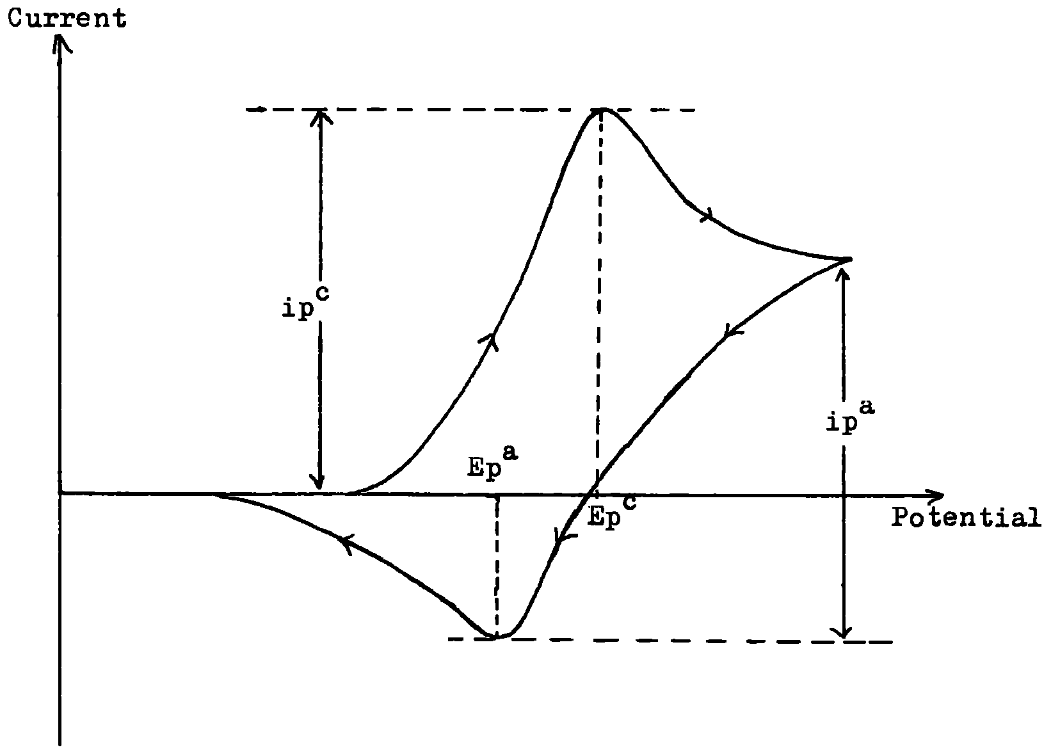
$$Ep^{a} - Ep^{c} = \frac{0.056}{n} \text{ Volts}$$

The peak potential is related to the polarographic $E_{\frac{1}{2}}$ by :

$$Ep^{c} = E_{\frac{1}{2}} - \frac{1.1RT}{nF}$$

It has also been shown[9] that the peak potentials are independant of scan rate, and the ratio of the peak currents, ip^{a}/ip^{c}, is unity.

Figure 4 Cyclic voltammogram of a reversible reduction: $O + ne^- \rightleftharpoons R'$



(b) Irreversible Reaction

If the product of the reduction process is not stable on the time-scale of the experiment, there will be less of it present on the reverse sweep, and so the reverse peak is smaller. i.e. $ip^a/ip^c < 1$. The separation between the forward and reverse peaks is seen to increase.

The timescale of the experiment can be changed by varying the potential scan rate. If the scan rate is increased, the chemical reaction following the electron transfer will have proceeded to a lesser extent, and so ip^a/ip^c increases until, in the limit, at very fast scan rates, the reaction may appear completely reversible. If the scan rate is decreased, more of the chemical reaction can take place, and, in the limit, the reverse peak disappears altogether, and the reaction appears completely irreversible.

The expected variations of a number of parameters with scan-rate have been calculated for a large number of reaction mechanisms,[9,10] so that information about the reaction sequence, and also rate constants[11], can be obtained by cyclic voltammetry.

New peaks may be observed on repetitive cycling, due to products of the chemical reaction, and these can be tentatively identified by matching their positions with those of likely products, run independently.

CHAPTER II

ELECTROCHEMICAL REACTIONS OF ORGANIC HALIDES

II.A INTRODUCTION

The electrochemistry of organo-halogen compounds has been extensively reviewed. (See, for example, the relevant sections in references 1-3.) This chapter provides a discussion of the main points, and a more extensive review of the polyhalides.

II.B REDUCTION

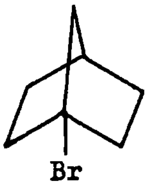
1. Monohalides

(a) Alkyl Halides

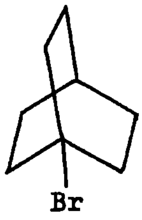
The reduction of alkyl halides is generally an irreversible, 2-electron process, independent of pH; resulting in the replacement of the halogen by hydrogen.[12] Coupled products have been observed in some cases,[13] and also the formation of organometallic compounds, involving the cathode material.[14] In the presence of carbon dioxide, anionic intermediates can sometimes be trapped, to give the corresponding carboxylic acid.[15]

The ease of reduction is in the order RI>RBr>RCl>RF. This has led to an analogy with the S_N2 displacement reaction,[16] (or S_N1, depending on steric factors); in which the electrons are considered to act as nucleophiles, attacking the back side of the carbon. It has been pointed out that this would be very difficult in crowded cases, such as (1) and (2).

(1)



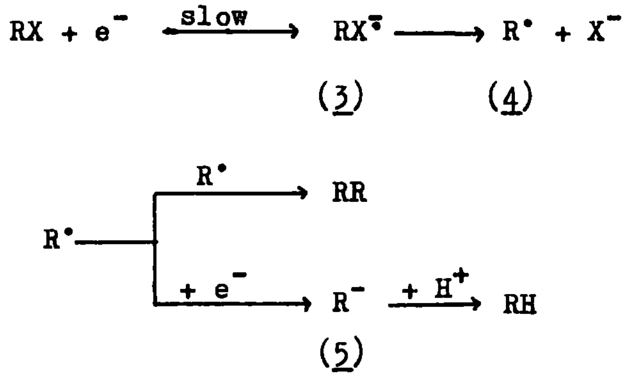
(2)



$E_{\frac{1}{2}}$ (v. Ag/Ag^+) -2.17V -1.79V

The reaction sequence shown in Scheme II.1, has been proposed for the reduction of alkyl halides.[17] The initial step is the transfer of an

Scheme II.1



electron to the unoccupied molecular orbital of lowest energy,(L.U.M.O.), to give the radical anion (3). It has been argued that if this is the potential determining step, as is suggested by its independence of pH; then there should be a relationship between the reduction potential and the energy of this orbital. Polarographic $E_{\frac{1}{2}}$'s for chloro-, bromo- and iodomethanes have been successfully correlated with the energies of the lowest unoccupied σ^* orbitals, calculated by the L.C.A.O.M.O. method.[18] This orbital is localised on the carbon-halogen bond.

The carbon-halogen bond then cleaves to give the radical (4), and further reduction gives the carbanion (5). The mechanism has been the subject of much discussion in the literature, which has by no means been resolved.[19] The observation of coupled products has been taken as evidence for relatively long-lived radical intermediates,[13] but these could be derived from attack by the carbanion on unreacted starting material:

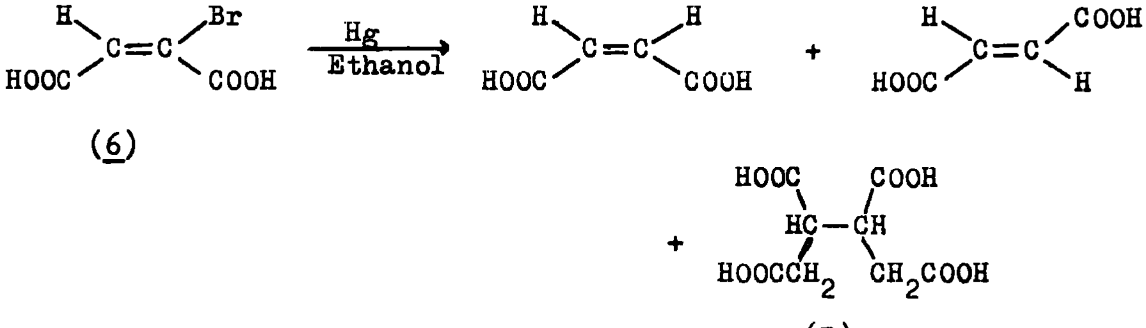
$$R^- + RX \longrightarrow RR + X^-$$

Another variation is that protonation of the radical anion (3) may occur prior to loss of halide. The resultant radical, RHX•, is more readily reduced than RX, and rapidly picks up another electron and loses X^-, to give RH. This is known as solvent-assisted reduction.

(b) Vinyl Halides

The reduction of vinyl halides generally occurs at more negative potentials than the corresponding alkyl halides. The products are normally similar, with replacement of the halogen by hydrogen but, when the double bond is conjugated with an aromatic system, it may be reduced itself.[20]

Cis-trans isomerisation may take place, as in the reduction of monobromomaleic acid (6), which also gives the dimeric product (7).[21]

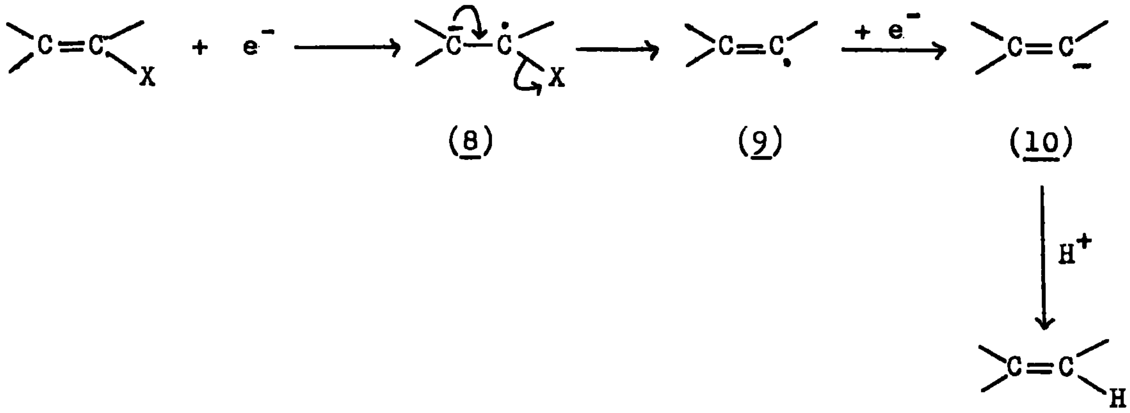


(6)

(7)

The mechanism shown in Scheme II.2 has been suggested to explain the cis-trans isomerisation.[20]

Scheme II.2



(8) (9) (10)

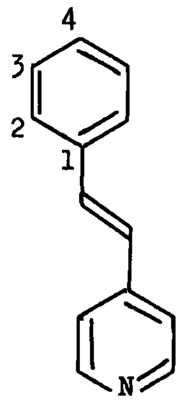
Addition of an electron to the lowest unoccupied π^* molecular orbital gives the radical anion (8). This has free rotation around the carbon-carbon bond, and so can lead to cis or trans products. Elimination of X^- gives the vinyl radical (9), which is further reduced to the vinyl carbanion (10), and subsequently protonated. Observation of the dimeric product from (6) was taken as evidence for the vinyl radical (9). However, as with alkyl halides, a route involving attack by the anion (10) on starting material could be envisaged, with subsequent reduction of the product giving (7).

Calculations on chloroethylenes,[18] however, show that the substitution of hydrogen by chlorine in ethylene hardly effects the energy of the lowest unoccupied π^* orbital, while considerably lowering σ energies. The result is that, according to the method used, the L.U.M.O. is in fact a σ^* orbital. It may be that whether the L.U.M.O. is a π^* or σ^* orbital depends greatly on the substituents present.

(c) Aryl Halides

The reduction of aryl halides is also more difficult than alkyl halides and similar to vinyl halides. It generally gives benzene as the product, in a 2-electron process. Thus, bromobenzene gives benzene in quantitative yield, but in the presence of carbon dioxide the intermediate anion can be trapped to give some benzoic acid.[2]

Calculations on chlorobenzene show that the first electron should again go into a σ^* orbital.[18,22] This is in contrast with the approach of another group.[23,24] They have related the rates of decomposition of the radical anions of 4-styryl pyridine derivatives to the free electron density in the lowest unoccupied π^* orbital of the parent compound (11).

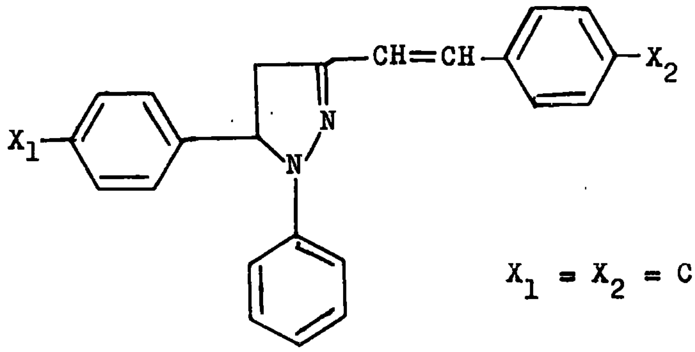


(11)

Position	Free electron density
1	0.031
2	0.070
3	0.004
4	0.085

They found that Br and Cl are rapidly lost from the 4-position on reduction, whereas the 3-chloro compound gives a reversible wave.[23]

The same workers have also used the free electron density of the π^* orbital to predict which halogen is lost on reduction of (<u>12</u>).[25]



$X_1 = X_2 =$ Cl or Br

(<u>12</u>)

They find that X_2 is lost, as predicted.

The polarographic half-wave potentials of a number of substituted aryl halides have been found to give reasonably linear correlations with the Hammett substituent constants.[26] The lines have positive slopes, which is evidence that the potential is determined by formation of a negatively charged transition state i.e. the initial radical anion.

A mechanism has appeared for the formation of coupled products, other than by radical coupling or anionic attack on the starting material. Strong evidence exists that the 4,4'-dicyanobiphenyl produced during reduction of p-fluorobenzonitrile, is formed via coupling of radical anions, followed by loss of two F^- ions.[27] This may prove to be a general mechanism, as it has received little consideration in the past.

2. Dihalides

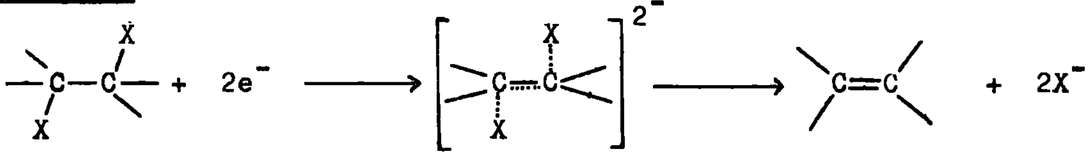
(a) Vicinal Dihalides

(i) Aliphatic

The electrochemical reduction of aliphatic vicinal dihalides generally resembles the reduction with zinc or sodium, giving the corresponding alkene.

The fact that 1,2-dibromoethane can be reduced to ethylene using 75% aqueous dioxane as solvent,[28] means that anionic intermediates are unlikely, as these would be trapped. A concerted mechanism is usually invoked, (Scheme II.3), in which the transition state has a new bond being developed,(13).[29]

Scheme II.3



(13)

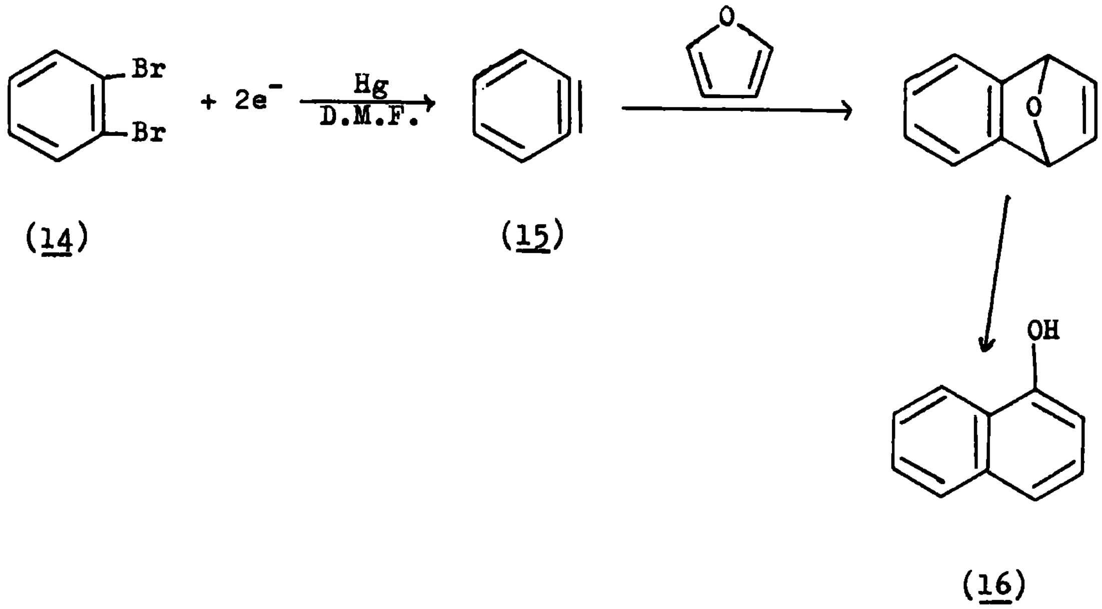
The fact that they are reduced at less negative potentials than the corresponding monohalides also suggests that a lower energy, concerted route is available to them.

(ii) Vinylic

1,2-Dihaloalkenes undergo a similar 2-electron reduction to acetylenes, which are reduced at more negative potentials. In general, trans dihalides reduce at more positive potentials than the cis isomers.[30]

(iii) Aromatic

o-Dibromobenzene (14) eliminates both bromines in a single polarographic step, to give benzene.[31] In the presence of furan,the benzyne (15), which is believed to be an intermediate, can be trapped to give α-naphthol (16) in small yield.


(14) (15) (16)

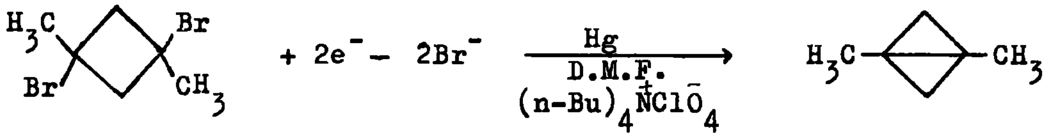
(b) α,ω-Dihalides

(i) Aliphatic

In many cases, halogens separated by more than two carbon atoms are reduced independently, to give the corresponding hydrocarbon. Thus, reduction of 1,5-dibromopentane in D.M.F. yields pentane.[32]

There are also a number of examples where small, strained rings are formed.[32]

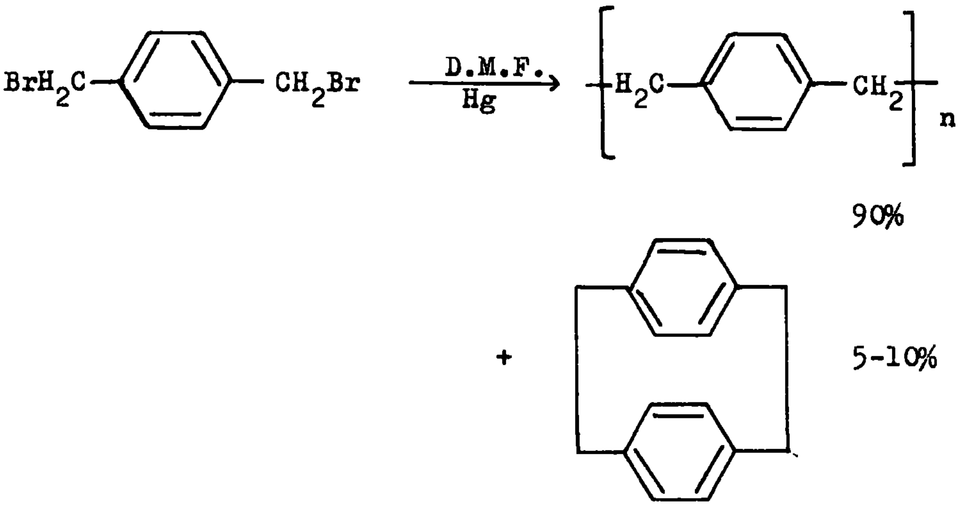
e.g.



Although these were originally explained as proceeding via anionic intermediates, which undergo cyclisation more rapidly than protonation; it now seems likely that they proceed in a concerted manner, like vicinal dihalides.[2]

The formation of polymers has also been reported.[33]

e.g.



This is believed to proceed via xylylenes, which dimerise or polymerise.

(ii) Aromatic

In general, m- and p- dihalobenzenes show two polarographic waves, with stepwise replacement of halogen, to give benzene.[31]

p-Fluoroiodobenzene is unusual, in that it shows two polarographic waves at -0.72V and -1.66V (v. S.C.E.), whereas fluorobenzene could not be reduced.[34] This can only mean that the fluorine is lost first, giving iodobenzene, which is the reverse of that expected.

3. Polyhalides

(a) Geminal

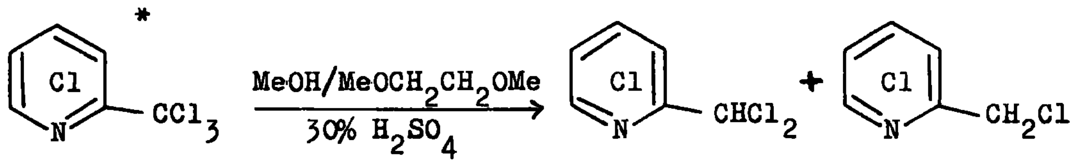
An increase in the number of halogens attached to the same carbon atom makes the reduction easier. The reduction proceeds in a series of 2-electron steps, with replacement of successive halogen atoms by hydrogen. Control of the potential can lead to the isolation of the product from an individual step, as in the reduction of trichloroacetic acid (17).[35]

$$\underset{(\underline{17})}{CCl_3COOH} + 2e^- \xrightarrow[aq.NH_4^+/NH_3]{Hg} \underset{100\%}{CHCl_2COOH}$$

Polarographic experiments in D.M.F. show that, in the absence of proton donors, only one electron is transferred, with subsequent loss of chloride; but products have not been isolated.[36] Trifluoroacetic acid shows only reduction of the proton.[37]

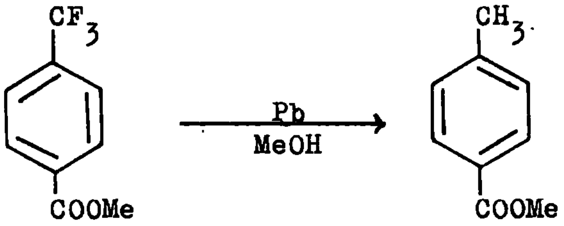
Esters of the type: R_FCOOEt also show a one-electron reduction in D.M.F.[38] It is suggested that the electron transfer is to the carbonyl function, but results in loss of F^-. Reduction becomes easier on increasing the size of the R_F group. The authors commented that this follows the order of stability of the R_F^- carbanion, and explained it similarly, by the inductive influence of fluorine stabilising a negative charge.

The side chains of perchloro- 2-methyl,(<u>18</u>), and 4-methyl-pyridine can be reduced in protic media.[39]



(<u>18</u>)

Similar reductions have been performed on the CF_3 group, but partial defluorination could not be achieved:[40]



It is difficult to say from polarography whether the reduction of gem

---

* The symbol Cl at the centre of the ring is used to mean that all positions carry chlorine, unless otherwise indicated.

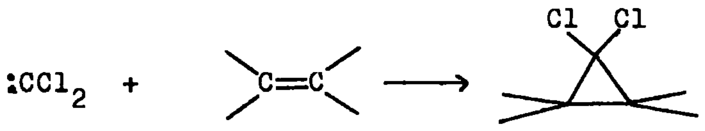
polyhalides proceeds via radical or anionic intermediates, but the results of preparative electrolyses generally agree better with the latter.

The reduction of perfluoro-n-hexyl iodide (19) in D.M.F. yields the organomercuric compound (20).[41] From polarography and cyclic voltammetry, the authors concluded that it is formed via a reaction between (19) and polarised mercury, to give $C_6F_{13}HgI$, which is then reduced to (20).

$$\underset{(19)}{C_6F_{13}I} \xrightarrow[\text{D.M.F.}]{\text{Hg}} \underset{(20)}{(C_6F_{13})_2Hg}$$

Reductions in aprotic solvents can lead to products derived from carbene intermediates as, for example, from carbon tetrachloride:[42]

$$CCl_4 + 2e^- \xrightarrow[-20^{\circ}C]{Hg, CH_3CN} {}^-CCl_3 + Cl^- \longrightarrow :CCl_2 + Cl^-$$



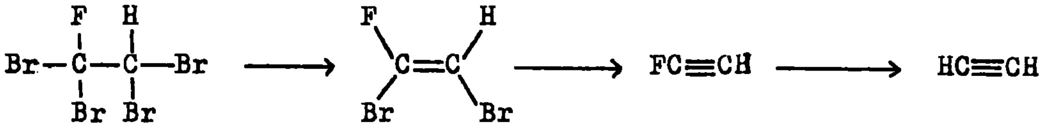
Tetrafluoroethylene (22) has been obtained in the reduction of 1,1-dichloro-2,2-difluoroethylene (21), via difluorocarbene.[43]

$$\underset{(21)}{CF_2{=}CCl_2} \xrightarrow[-70^{\circ}C]{Cu, LiClO_4} \underset{(22)}{CF_2{=}CF_2} + CF_2H{-}CCl_2H$$

Major products

(b) Formation of Multiple Bonds

The elimination of two halogen atoms from adjacent carbon atoms to produce unsaturation can be applied to polyhalogenated systems. Reduction of 1,1,2,2-tetrabromofluoroethane (23) gives all three expected products (24), (25) and (26).[44]



(23) (24) (25) (26)

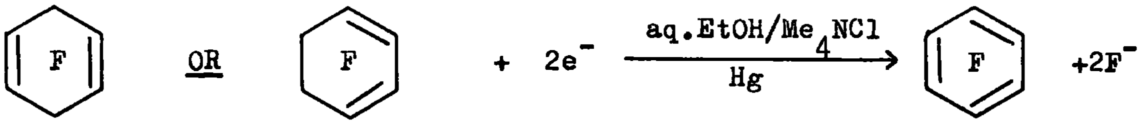
Fluoro-olefins have been prepared by electrochemical dehalogenation of Freons in aqueous organic solvents at a lead cathode, in the presence of lead compounds.[45]

$$\text{e.g.}\quad CF_2ClCF_2Cl + 2e^- \xrightarrow[\text{Pb, Pb(NO}_3)_2\ \ -8^\circ C]{\text{aq.KOH/iso-PrOH}} CF_2{=}CF_2 + 2Cl^-$$

The reduction of 1,2,3,4,5,6-hexabromocyclohexane (27) gives benzene.[46]

$$\underset{(27)}{C_6H_6Br_6} + 6e^- \longrightarrow C_6H_6 + 6Br^-$$

Similarly, aromatic fluorocarbons can be prepared by the reduction of fluorinated cyclohexenes and cyclohexadienes.[47,48] For example, reduction of (29) or (30) gives hexafluorobenzene (28).



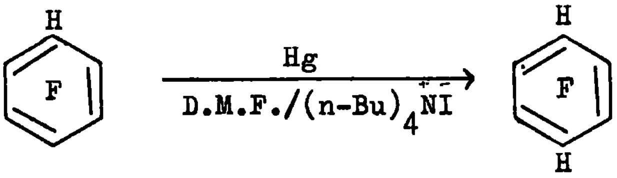
(29) (30) (28)

A stepwise mechanism was proposed for this reaction, with a slow one-electron transfer, followed by slow loss of F^- to give a radical, which would be the same for either (29) or (30). This is then rapidly reduced further and loses F^- to give (28).

(c) Aromatic Compounds

The reduction of a number of polyfluoro- and polychlorobenzenes has been studied polarographically.[49,50] The results for fluorinated compounds in aqueous dioxane[49] led to the conclusion that protonation immediately followed the initial one-electron transfer i.e. solvent-assisted reduction.(See p.14.)

Preparative experiments on pentafluorobenzene (31),[50] at controlled potential, show it to be reduced to 1,2,4,5-tetrafluorobenzene (32) exclusively. The position of reduction is thus the same as that of nucleophilic attack.[52,53] In this reaction, tributylamine was detected in the product, demonstrating that the electrolyte acts as a source of protons, by the well-known Hofmann elimination reaction, whereby a proton is abstracted from a beta- carbon atom in a tetra-alkylammonium salt.

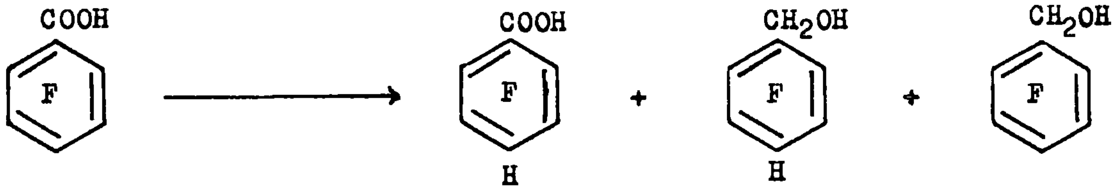


(31) (32)

A large number of polychlorinated benzenes and biphenyls have been shown to give successive replacement of the chlorine atoms, when reduced in D.M.S.O./Et$_4$NBr.[54,55] To try and throw some light on the controversy over which orbital the first electron is transferred into, molecular orbital calculations were performed on all of the chlorinated benzenes, using the C.N.D.O./2 method.[22] It was found that the energies of the σ^* L.U.M.O. and π^* L.U.M.O. were roughly equal. However, when calculations were performed on the radical anions, they showed that the extra electron should have entered a σ^* orbital.This orbital is found to have electron density localised in the C-Cl bond which undergoes cleavage to give the isolated product. Furthermore, when several products were formed, the σ^*

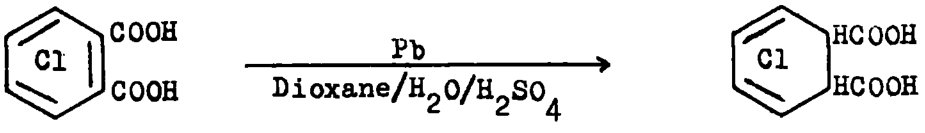
orbital had electron density in all of the C–Cl bonds involved, and the product ratios could be correlated with the electron density. These calculations appear to provide very strong evidence that the first electron is transferred to a σ^* orbital when chlorobenzenzenes are reduced. While this may be a correct picture, Dr. D.T.Clark, in these laboratories, feels that the programme used may give misleading results. Certainly, his calculations on fluorinated benzenes show that the extra electron in their radical anions is in a π^* orbital.[56]

The reduction of some halogenated aromatic acids has been investigated. Pentafluorobenzoic acid (33) is reduced to the three products (34),(35) and (36) in various yields, depending on the potential, solvent, electrolyte and electrode material.[57] The reduction of pentafluorobenzaldehyde also gives (35) and (36), at less negative potentials, explaining why none is isolated as an intermediate. Tetrafluorobenzoic acids with different para substituents also show elimination of the para substituent, and the ease of this reduction parallels the ease of nucleophilic displacement.



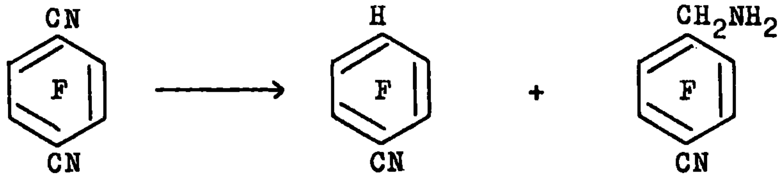
(33) (34) (35) (36)

In contrast to these results, tetrachlorophthalic acid (37) has been reduced to (38), with partial saturation of the ring.[58]



(37) (38)

The reduction of perfluoro-1,4-dicyanobenzene (39) proceeds with either fission of a C–CN bond to give (40), or reduction of a nitrile group to give (41), depending on the conditions.[59]



(39) (40) (41)

Finally, perfluoro-biphenylmercury (42) has been shown to be reduced to pentafluorobenzene (31).[60]

$$\underset{(42)}{(C_6F_5)_2Hg} \xrightarrow[\text{MeOH/NaOAc}]{\text{Hg}} \underset{(31)}{C_6F_5H}$$

II.C OXIDATION

Much less work has been done on the oxidation of organic halides, owing to the fact that, in contrast to reduction, the presence of electronegative groups makes oxidation more difficult.

1. Aliphatic Halides

(a) Monohalides

The oxidation of alkyl iodides in acetonitrile leads to N-alkylacetamides (43) and iodine.[61] The reaction mechanism (Scheme II.4), is thought to involve carbocations.

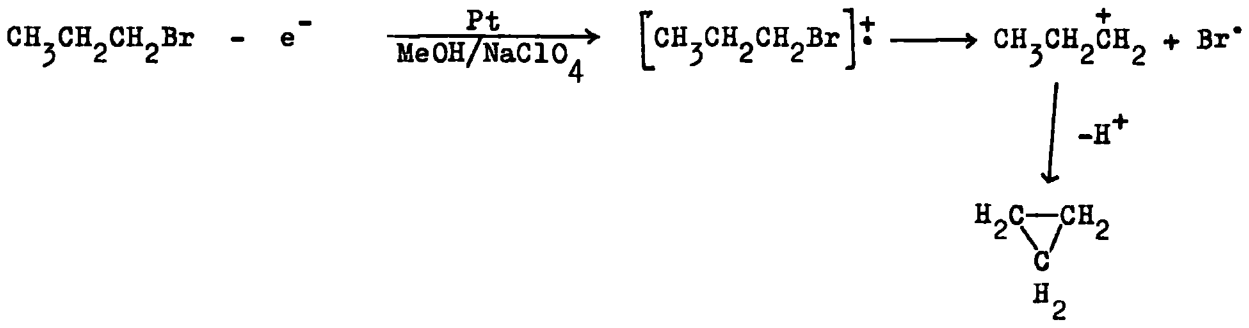
Scheme II.4

$$RI - e^- \longrightarrow RI^{+\bullet} \longrightarrow R^+ + I^\bullet$$

$$R^+ + CH_3CN \longrightarrow RN{=}\overset{+}{C}CH_3 \xrightarrow{+H_2O} CH_3CONHR$$

(43)

The carbocation exists long enough to rearrange, so that oxidation of neopentyl halide leads to N-tert-pentyl acetamide. Also, the oxidation of propyl bromide in methanol leads to a 78% yield of cyclopropane:[62]



More recently, a concerted mechanism for the oxidation of alkyl iodides has been suggested, with solvent and neighbouring group participation.[63,64]

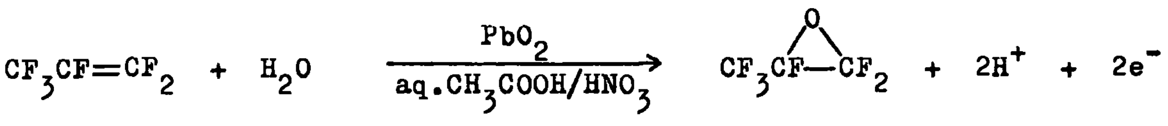
(b) Polyhalides

The oxidation of polyfluorocarboxylic acids has been used to generate polyfluoroalkyl radicals, which were then added to olefinic double bonds.[65] The oxidation does not involve the C—F bonds, however, but is an extension of the well-known Kolbe electrolysis of carboxylate anions:

$$RCOO^- - e^- \longrightarrow RCOO^\bullet \longrightarrow R^\bullet + CO_2$$

$$R^\bullet + R^\bullet \longrightarrow RR$$

The oxidation of hexafluoropropene (44) to its epoxide (45) has been reported.[66]



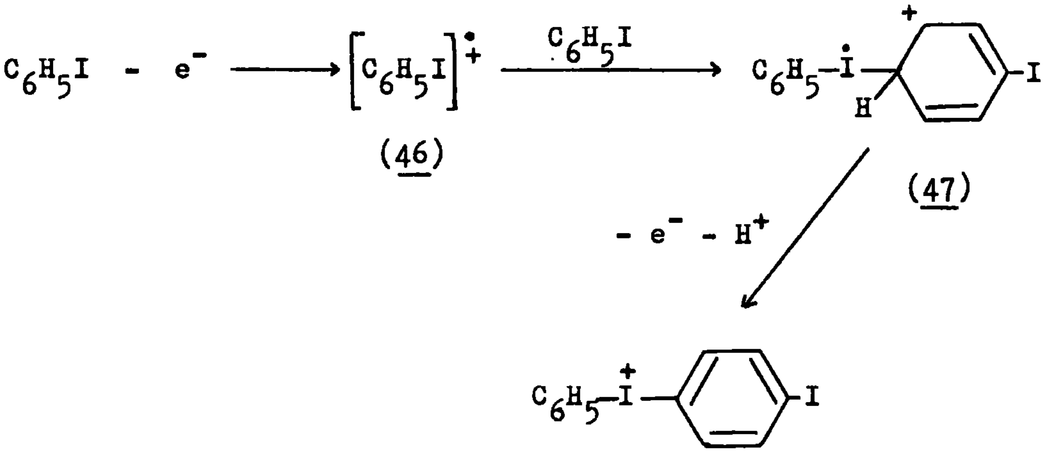
(44) (45)

2. Aromatic Halides

(a) Monohalides

Aryl iodides do not undergo carbon-iodine bond scission on oxidation,[61] but the major reaction is coupling to iodonium salts (48),(Scheme II.5).

Scheme II.5

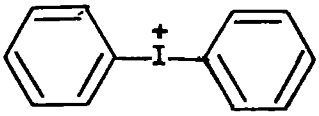


(46)

(47)

(48)

The iodonium salt (48) might have been formed by coupling of the radical cation (46), but in the presence of benzene it is found that the radical cation is trapped to give the diphenyliodonium ion (49), by an analogous route to that above.



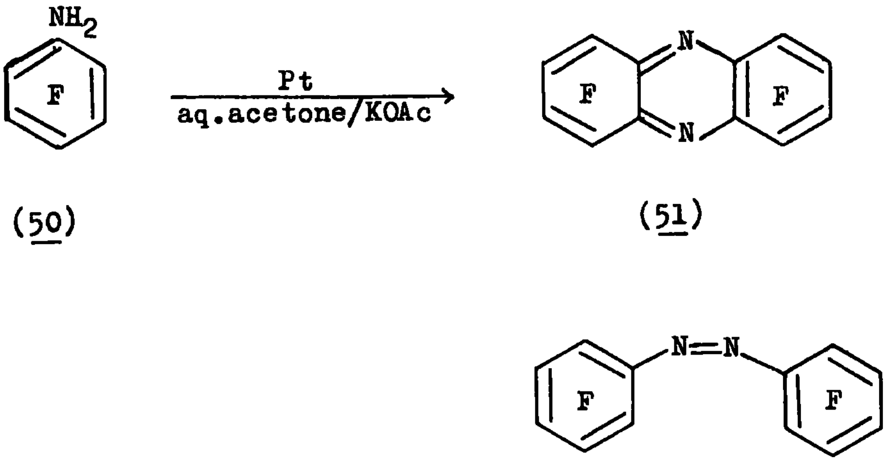
(49)

If the perchlorate salt of (49) is isolated, its hydrolysis in aqueous solutions provides a route to phenol.[68]

(b) Polyhalides

In general, polyfluoroaromatic compounds are too difficult to oxidise in conventional solvent systems, but voltammetric data has been reported for a series of fluoroaromatic compounds in fluorosulphonic acid/acetic acid mixtures.[69] At low temperatures, the radical cations are stable indefinitely, but at room temperature fluorosulphonate esters can be prepared.

In contrast, fluoroaromatic compounds containing the -NH_2 group have been successfully oxidised.[70,71] For example, pentafluoroaniline (50) gives octafluorophenazine (51) and decafluoroazobenzene (52).[70]



(50)

(51)

(52)

DISCUSSION

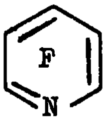
CHAPTER III

ELECTROCHEMICAL REDUCTION OF SOME POLYHALOGENATED PYRIDINE DERIVATIVES

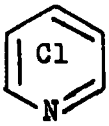
III.A INTRODUCTION

The electrochemical reduction of monohalogenopyridines results in the replacement of the halogen by hydrogen, in a pH dependent reaction.[72] Polychloropyridines can be reduced in protic media, with replacement of the 4-chlorine.[73] No work has been reported on polyfluoropyridines, however, although some other fluorinated aza-aromatics have been studied by cyclic voltammetry.[74]

The aim of the work described here was to investigate the reduction of pentafluoropyridine (53) and pentachloropyridine (54) in aprotic media, with a view to generating radical anion intermediates and investigating their reactions.



(53)



(54)

The solvent generally used was dimethylformamide (D.M.F.), which is widely used for reductions because of its high cathodic limit (see p.5). Tetraethylammonium fluoroborate was used as the electrolyte, and mercury as the cathode material. All potentials quoted are relative to the saturated calomel electrode (S.C.E.).

The experimental techniques and apparatus are described fully in Chapter VI.

III.B PENTAFLUOROPYRIDINE AND SOME RELATED COMPOUNDS

1. Reduction in Aprotic Media

The reduction of pentafluoropyridine (53) in D.M.F. at -1.8V gave the dimer octafluoro-4,4'-bipyridyl (56) as the only isolated product. This was identified by comparison with an authentic sample.[75]

The reaction was performed on a number of occasions, varying the amount of (53) used, the number of electrons/molecule supplied (faradays/mole), and the work-up method. There was some difficulty in isolating all of the dimer (56) produced, because of its tendency to transfer with the solvent under reduced pressure. The highest yield obtained was a current efficiency (C.E.) of 52%, after passage of only 0.18 electrons/molecule, but this might possibly be improved. (For an explanation of C.E. see p.7). In general the efficiency appears to decrease as the number of electrons/molecule passed is increased, i.e. at higher conversions. This is accompanied by an increase in tar formation and this was shown by thin layer chromatography to be a multicomponent mixture. This can be explained by the fact that, as was shown later, (56) is itself reducible at the potential used and polymeric material may result.

The bipyridyl (56) was also produced by reduction of pentafluoropyridine in sulpholane, when separation from the very involatile solvent was possible by flash vacuum distillation. A 48% C.E. was obtained after passage of 0.71 electrons per molecule of (53). No satisfactory result was obtained using acetonitrile as solvent; the current was variable during the electrolysis and a lot of tarring occurred.

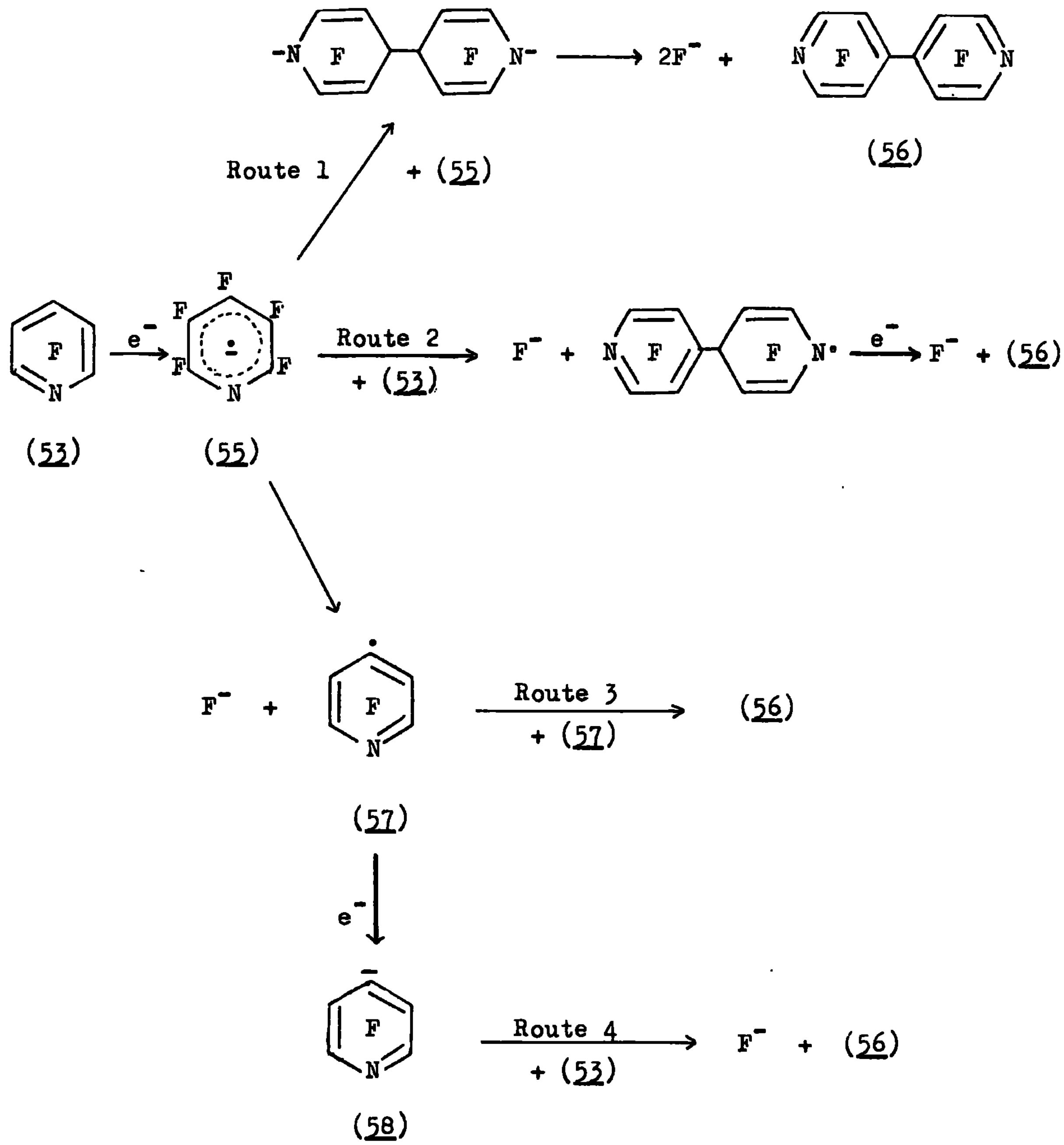
The reductions in D.M.F. and sulpholane proceed with the production of a turquoise colour , which was later identified as being due to the radical anion of the bipyridyl (56). (See p.39).

2. Mechanism of the Reduction in Aprotic Media

Possible routes for the formation of (56) are shown in Scheme III.1 overleaf. In all cases one electron is required for each molecule of (53) reduced, i.e. two electrons for each molecule of (56) formed. The current efficiency was calculated on this basis.

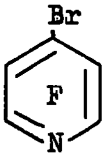
Routes 1 and 3 involve dimerisation of the radical anion (55) or radical

Scheme III.1

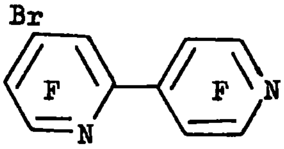


(57) respectively. Routes 2 and 4 involve nucleophilic displacement of F^- from unreduced (53) by (55) or the carbanion (58) respectively. It is known that pentafluoropyridine undergoes nucleophilic substitution in the 4- position.[76] None of these routes can be eliminated for pentafluoropyridine.

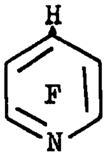
4-Bromotetrafluoropyridine (59), however, undergoes nucleophilic



(59)



(60)



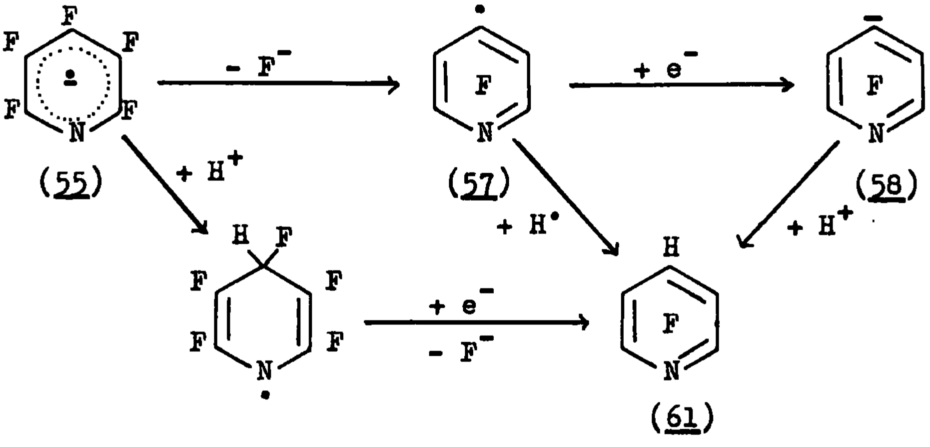
(61)

substitution in the 2- position,[75] so that routes 2 and 4 would lead to the bipyridyl (60). When (59) was reduced only a small amount of dimeric product was obtained but this was shown conclusively to be (56) and not (60). Thus routes 2 and 4 can be ruled out for (59), and the reduction of (53) probably occurs the same way, via route 1 or 3. The reduction of (59) also gave a small yield of the 4-H compound (61), which was obtained from the reduction of (53) in the presence of a proton donor. (See below).

3. Reduction in the Presence of a Proton Donor

Hydroquinone is said to be a good proton donor for use in D.M.F. solutions.[51] When pentafluoropyridine (53) was reduced at -2.4V in D.M.F. containing hydroquinone, the course of the reaction was altered. The turquoise colouration observed previously was not seen and the product obtained was 4-H-tetrafluoropyridine (61), identified by comparison with an authentic sample.[77] After passage of 0.40 electrons/molecule, (61) was obtained with a current efficiency of 46%, assuming a two-electron process. Possible routes for the production of (61) are shown in Scheme III.2, starting from the radical anion (55).

Scheme III.2



Abstraction of H• by the radical (57) is an unlikely route as this could happen in the absence of a proton donor, besides which reductive dehalogenation is normally a two-electron process. The carbanion (58) is the final link in the chain and protonation of this would not prevent the dimerisation of the intermediates (55) and (57). No dimer is produced, which leaves protonation of the radical anion (55) as the most likely route to (61). This protonation must occur more rapidly than dimerisation of (55) or loss of F^-. This is the so-called 'solvent assisted' reduction mechanism, (see p.14).

4. Reduction in the Presence of Carbon Dioxide

Carbon dioxide has been used extensively as a trap for carbanions, to produce carboxylic acids. Its use to trap carbanions generated electrochemically was mentioned in Chapter II (pages 13 and 16). It has also been used to trap radical anions, as for example during the reduction of activated olefins:[78]

$$\begin{tikzcd}
CH_2{=}CHX + e^- \arrow[r] & \left[CH_2{=}CHX\right]^{\dot{-}} \arrow[r, "CO_2"] & {}^-O_2CCH_2\dot{C}HX \arrow[r, "e^-"] & {}^-O_2CCH_2\bar{C}HX \arrow[d, "CO_2"'] \\
 & & & {}^-O_2CCH_2CHXCO_2^-
\end{tikzcd}$$

$X = CH_3CO_2, COCH_3, CN$

It was felt, therefore, that carbon dioxide might react with any negatively charged species formed during the reduction of pentafluoropyridine (53). When the reaction was performed, by using D.M.F. saturated with carbon dioxide as the solvent, a dirty green colouration was formed instead of the normal turquoise colour. This showed that the carbon dioxide had altered the course of the reaction, but was in contrast to the successful trapping experiments performed later on pentachloropyridine (54), in which the solution remained clean and colourless throughout. After passage of 0.77 electrons/molecule, removal of the solvent, and acidification of the water-soluble part of the residue, no acidic product could be extracted. Only a small yield of the bipyridyl (56) was obtained,(7% C.E.), and a large amount of intractible residue. It is not understood how the carbon dioxide affects this reaction.

In another experiment octafluoro-4,4'-bipyridyl (56) was reduced under identical conditions at -1.2V. The carbon dioxide did not appear to affect the reaction, as the turquoise colour of the radical anion of (56) was produced. This colour persisted until the reaction was worked up, when the solution turned brown. It appears that the radical anion is unstable in the atmosphere. Again no acidic product was obtained.

Thus,neither the stable radical anion of (56), nor the rather more unstable one of (53) can be trapped with carbon dioxide to give acids.

5. Voltammetry

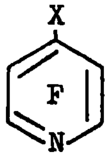
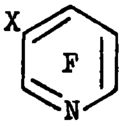
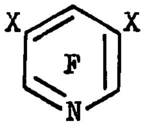
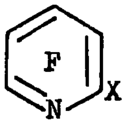
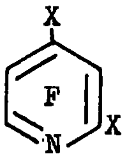
An explanation of the basic principles of voltammetry appears in Chapter I. Polarographic $E_{\frac{1}{2}}$'s could not be measured for the pyridines studied as they caused fouling of a dropping mercury electrode. For this reason voltammograms were recorded on 4mM solutions using platinum wire electrodes in unstirred solutions. These were recorded using a Beckmann Electroscan 30 electroanalytical instrument, employing sweep rates between 4 and 100mV/sec. The half-peak potentials, $Ep_{\frac{1}{2}}$, were taken as a guide to the polarographic $E_{\frac{1}{2}}$'s. Crude cyclic voltammetry could also be performed using this instrument by manually reversing the sweep direction after the peak.

Cyclic voltammetry at sweep rates of up to 10 V/sec was performed using more sophisticated apparatus at the Electricity Council Research Centre, Capenhurst. The solutions used were 10mM and the electrodes were again platinum.

(a) Single Sweep Voltammetry

The aim of this work was to measure the $Ep_{\frac{1}{2}}$'s of a number of fluorinated pyridines, to see if any trends could be observed which would provide

<u>Table III.1</u> $Ep_{\frac{1}{2}}$ in Volts measured at 20mV/sec sweep rate.

X					
F	←		-1.80V		→
Cl	-1.65V	-1.90V	-1.85V	-1.79V	
Br	-0.81V			-1.25V	
I	-0.72V				
H	-1.96V	c	c	-1.94V	
CF_3		-1.69V	-1.59V		
C_2F_5	-1.38V				
C_3F_7	-1.38V				-1.16V
C_5F_4N	-1.18V [a]	-1.71V [b]			
C_6F_5	-1.45V				
NH_2	c				

a Octafluoro-4,4'-bipyridyl (<u>56</u>).

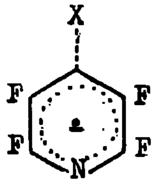
b Octafluoro-3,3'-bipyridyl (<u>62</u>).

c Peak at a more negative potential than the cathodic limit of ca. -2.0V.

evidence for the structure of their radical anions. These $Ep_{\frac{1}{2}}$'s were found to vary with sweep rate by varying amounts, which is to be expected from irreversible reductions. The variations were not large enough to alter the trends observed, however. The values obtained at a sweep rate of 20mV/sec are shown in Table III.1. The D.M.F. used must have been slightly wet, as the cathodic limit was only -2.0V.

Octafluoro-4,4'-bipyridyl (<u>56</u>) was the only compound to have $Ep_{\frac{1}{2}}$ invarient with sweep rate. This was later shown to be a reversible one-electron transfer. (See next section). As the other compounds gave peak heights roughly twice as high, these must have been due to two-electron reductions. Thus, the traces of water present appear to have been enough to cause reduction to the hydro- compounds in these very dilute solutions. Certainly the pyridines gave no colour formation, unlike the large-scale reduction of pentafluoropyridine (53).

It has been argued that for irreversible reductions, as long as the electron transfer is the potential determining step, the $E_{\frac{1}{2}}$'s for a series of related compounds can be related to the energies of their lowest unoccupied molecular orbitals, (L.U.M.O.'s).(See p.14). These must be related to the radical anions formed by putting an electron into them. Thus the easier the reduction is, the lower the energy of the radical anion. For the above condition to apply there must be no carbon-halogen bond breaking in the potential determining step, or the strength of the C–X bond involved becomes important. i.e. The transition state must not be of the type:



Bearing these effects in mind, let us examine the series of pyridine derivatives in Table III.1. If the $Ep_{\frac{1}{2}}$'s are compared with pentafluoropyridine (53), it is evident that altering the substituent in the 4-position has a much greater effect than in the 2- or 3- positions. Whether this reflects a change in energy of the radical anion or the ease of C–X bond breaking, it can only mean that in the intermediate the greatest amount of charge is located in the 4- position. This agrees with the preparative experiments on (53), where reduction occurs exclusively in the 4- position.

The order of increasing ease of reduction for 4- substituents is the same as that normally observed for alkyl and aryl halides, (see Chapter II).

i.e. $H<F<Cl<Br<I$. This may reflect the ability of the substituent to stabilize a negative charge on the 4- carbon atom and lower the energy of the radical anion. The order of carbanion stabilizing ability of these substituents normally observed is $H<F<Cl<Br\simeq I$.[76] This explanation would also explain how other electron-withdrawing groups in this position facilitate reduction when they are unlikely to be eliminated themselves, and also why the electron-donating NH_2 group makes reduction harder. However, the order observed for the halogens is quite consistent with their C—X bond strengths.

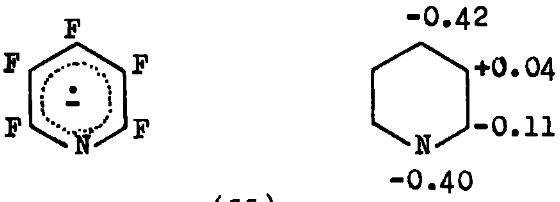
Substitution of more readily reduced chlorine in the 3- position does not make reduction easier, suggesting that little charge goes into this position. There is a particularly striking difference between octafluoro-4,4'-bipyridyl (56) and the 3,3'-bipyridyl (62), which is dealt with more fully in the next section. This is best explained by stabilization of a negative charge in the 4- position over two pyridine rings in (56) but not in (62).

Substitution of chlorine in the 2- position again does not make reduction easier. The electron-withdrawing C_3F_7 group does have some effect, but not as much as in the 4- position, suggesting that there is much less charge here. A bromine in this position has much less effect than in the 4-position, but makes the reduction markedly easier than that of pentafluoropyridine. Perhaps the bromine directs the point of reduction to the 2- position in this case.

Conclusion

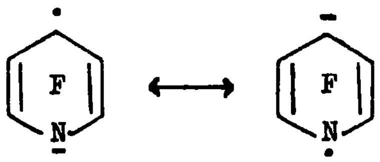
Although it is not intended to imply that the $Ep_{\frac{1}{2}}$'s observed have any quantitative thermodynamic significance, the trends clearly show that in most cases the charge in the intermediate is located on the 4- carbon atom rather than the 2- or 3- positions. It is not possible to say how much charge is located on the ring nitrogen.

In the light of these findings, it is interesting to compare the results with a calculation on the pentafluoropyridine radical anion (55).[56] This shows it to be a π radical anion, with the charge density shown below. Thus it has charge confined mainly to the 4- carbon and the ring nitrogen.



(55)

The calculation also agrees closely with the valence bond picture of the radical anion:



(b) Cyclic Voltammetry

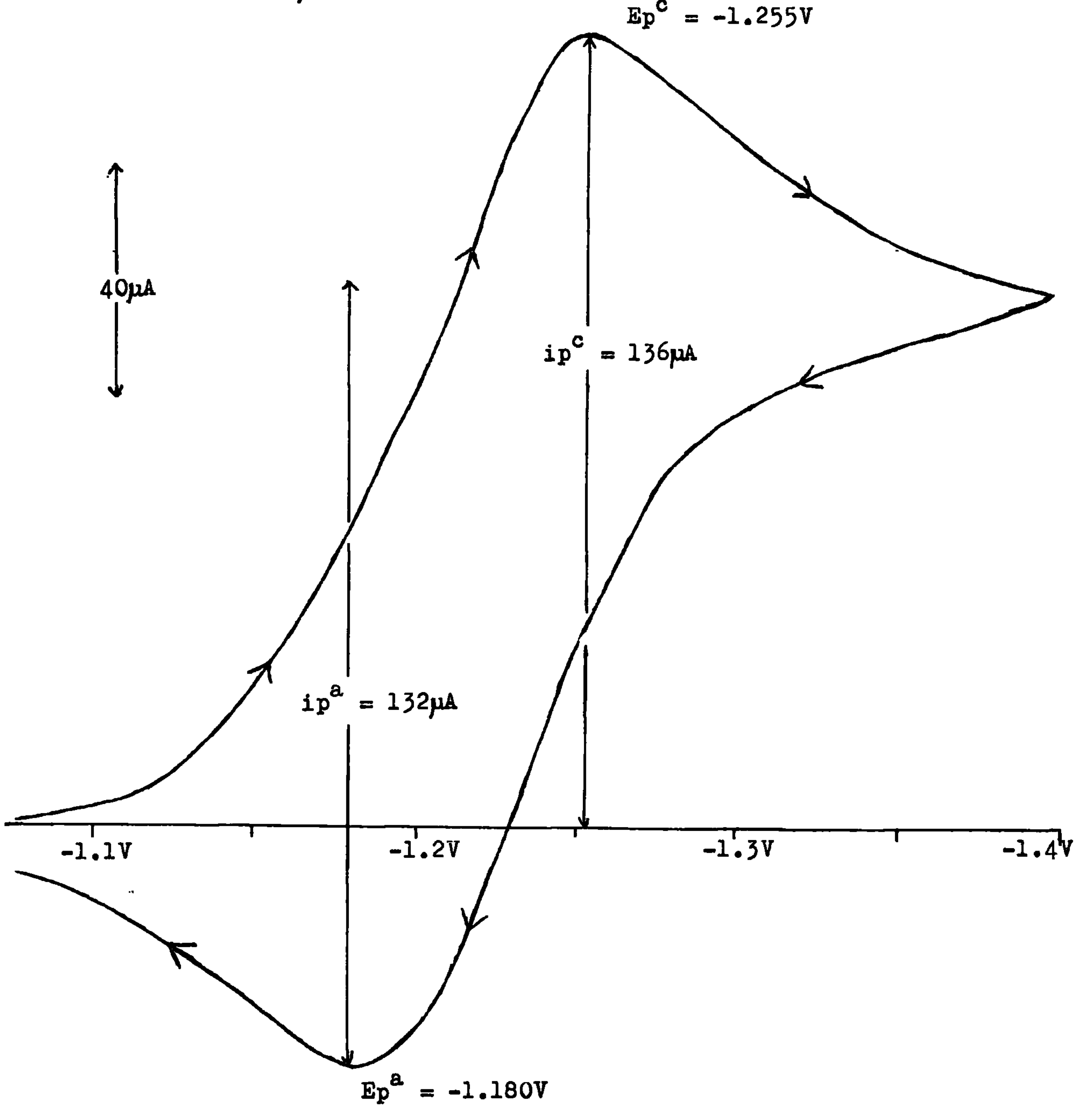
(i) Octafluoro-4,4'-bipyridyl (56)

The bipyridyl (56) was investigated using the Electroscan instrument. It gave a reversible reduction wave at sweep rates as low as 1mV/sec. A cyclic voltammogram recorded at 10mV/sec is shown in Figure III.1 overleaf.

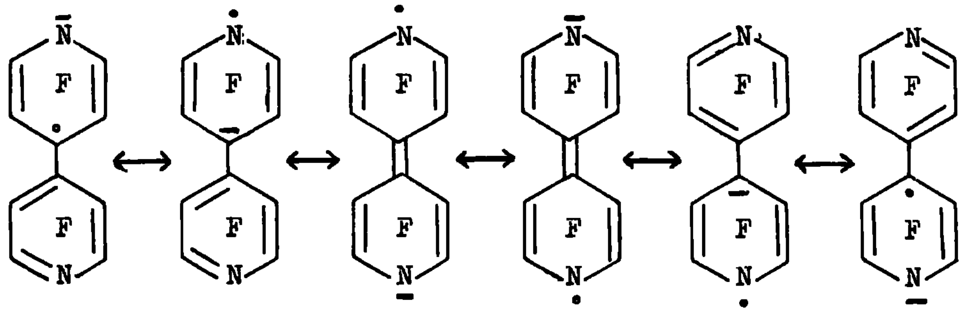
The cathodic and anodic peak currents are virtually identical, showing the chemical reversibility of the process. The peak separation, $Ep^{a} - Ep^{c}$, is too large, however, and when the value of 0.075V is inserted into the equation for a reversible reduction (p.10) a value of n of 0.75 is obtained. This is obviously a one-electron reduction and the increased peak separation from ideal behaviour is due to a slow electron transfer.

During the reduction a turquoise colour is formed at the cathode, which is discharged during the reverse sweep. This must, therefore be the colour of the very stable radical anion of (56). The great stability of the radical anion can be explained by the extra electron being

Figure III.1 Cyclic Voltammogram of Octafluoro-4,4'-bipyridyl (56) at 10mV/sec.



delocalised over both rings. In terms of valence bond theory a much greater number of resonance canonicals is then available, (see overleaf). This is interesting, as the bipyridyl (56) is thought to be nonplanar due to unfavourable interactions between the ortho fluorine atoms, and for two aromatic rings to be in conjugation coplanarity is necessary. The angle between the two rings in the unfluorinated compound, 4,4'-bipyridyl, has



Resonance canonicals of the radical anion of (56).

been calculated from ^{1}H n.m.r. measurements to be 30°.[79] It would be expected that the presence of fluorine in the ortho positions would increase this angle. It appears that the stabilization gained by delocalisation of the negative charge over two rings is sufficient to overcome these interactions and make the radical anion of (56) planar.

The conjugation between the rings of unreduced (56) was investigated by ultra-violet spectroscopy, which has been used successfully in biphenyls.[80] Benzene shows absorptions at 204nm ('E-band', ε 7,900) and 256nm ('B-band', ε 200). The presence of a chromophore in the molecule directly conjugated with the ring causes a strong bathochromic shift of the B-band (to longer wavelength), and the appearance of an intense K-band in the 200 - 250nm region. Thus the presence of an intense band at 252nm (ε 19,000) in biphenyl is taken to show that the two rings are conjugated. 2,2'-Dimethylbiphenyl shows only a B-band at 270nm (ε 800), showing the conjugation to be greatly decreased by the interactions between the two methyl groups forcing the rings out of coplanarity.

Pentafluoropyridine (53) shows a B-band at 256nm (ε 2,800). In (56) this is shifted to 281nm and increased in intensity to ε 8,200. This shows that there is some conjugation between the rings, but no new intense absorption was observed.

(ii) Octafluoro-3,3'-bipyridyl (62)

The 3,3'-bipyridyl (62) was investigated on the Electroscan instrument and gave an irreversible two-electron wave at scan rates up to 100mV/sec.

If the extra electron in the radical anion of (62) is confined mainly to the 1 and 4 positions it cannot be stabilized by conjugation with the second pyridine ring in the 3- position. Thus, (62) has an unstable radical anion and an irreversible reduction is observed. Also (62) has fluorine in the reactive 4- position and so behaves similarly to pentafluoropyridine.

The ultra-violet spectrum of (62) shows very little evidence of conjugation, the absorption at 262nm being hardly shifted from that of pentafluoropyridine at 256nm. There is an increase in intensity to ε 11,100, however.

(iii) Fluorinated Pyridines

Pentafluoropyridine and 2-bromopentafluoropyridine were investigated using the Electroscan instrument and both showed no reversibility at scan rates up to 100mV/sec.

A series of 4-X-tetrafluoropyridines (X = F, Cl, Br, I, C_2F_5, and H), 3-chlorotetrafluoropyridine and 3,5-dichlorotrifluoropyridine were also investigated at scan rates up to 10V/sec at E.C.R.C., Capenhurst. These all showed no reoxidation wave, and coloured layers formed around the cathode - turquoise in the case of pentafluoropyridine (53).

On continuous high-speed cycling new peaks appeared for the pentafluoro- , 4-chloro- and 4-bromo- compounds, due to products accumulating on the cathode. All three gave a pair of reduction/oxidation peaks with $Ep^c \simeq -1.29V$ and $Ep^a \simeq -1.13V$. This is about the correct position for the dimer (56), the peak separation increasing to 0.16V at these fast sweep rates because of the slowness of the electron transfer process. Other smaller peaks appeared in different places for the three compounds, which could not be identified. When water was added to the solution, these new peaks were no longer formed on continuous cycling, in agreement with the experimental observation that (56) was not formed from (53) in the presence of a proton donor.

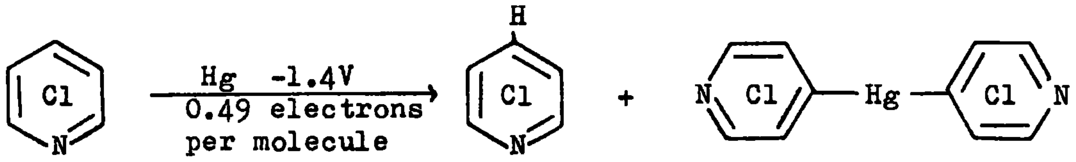
The 4-iodo- , hydro- , and perfluoroethyl- compounds gave no new peaks on continuous cycling. Thus, the iodo compound behaves differently to the other 4-halo- compounds. The hydro and perfluoroethyl compounds have no halogen to eliminate from the 4-position to give the dimer (56) and would, therefore, be expected to behave differently.

3-Chlorotetrafluoropyridine gave a small pair of peaks on continuous cycling at $Ep^{c} \simeq -0.89V$ and $Ep^{a} \simeq -0.65V$, possibly due to a dimer with the 3-chlorines still intact. The 3,5-dichloro- compound gave no such peaks. Possibly coupling in the 4-position is inhibited by the two adjacent chlorines for steric reasons, as is suggested in the next section for pentachloropyridine (54).

III.C PENTACHLOROPYRIDINE AND SOME RELATED COMPOUNDS

1. Reduction of Pentachloropyridine in D.M.F.

The reduction of pentachloropyridine (54) in D.M.F. takes a different course to that of pentafluoropyridine (53). On a mercury cathode the products are 4-H-tetrachloropyridine (63) and the organo-mercury compound (64).



(54) (63) (64)

Current Efficiency 57% 17%

The hydro- compound (63) was obtained as a mixture with (54) and identified by g.l.c. with mass spectroscopy. It was obtained pure from the trapping experiments with carbon dioxide described later. The replacement of the 4-chlorine is in agreement with results obtained in protic media.[73] The organo-mercury compound (64) was identified from its mass spectrum and elemental analysis and assigned the 4,4' structure solely by analogy with the formation of the 4-hydro compound. It has been prepared previously by reaction between tetrachloro-4-pyridyl lithium and mercuric chloride.[81]

Unlike pentafluoropyridine, only a trace of a bipyridyl was formed and was only detected by mass spectroscopy. It may be that the dimerisation reaction is inhibited by the presence of bulky chlorine atoms. Another difference was the formation of large amounts of hydro compound in the absence of any added proton donor. This must be derived from an intermediate which is a strong enough base to abstract a proton from the electrolyte. In view of the fact that the radical anion of pentafluoropyridine was not able to do this, it seems likely that (63) is formed from the corresponding carbanion.

Organo-mercury compounds are normally considered to derive from radical intermediates. Routes such as Scheme III.3 have been proposed to explain the production of both hydro and organo-mercury compounds in the same reaction.[82]

Scheme III.3

$$RX + e^- \longrightarrow RX^{\overline{\bullet}} \longrightarrow X^- + R^\bullet \xrightarrow{e^-} R^-$$

$$R^\bullet + Hg^o \longrightarrow RHg_n^\bullet \xrightarrow{RHg_n^\bullet} RHgR + Hg_n^o$$

$$RHgR + e^- \longrightarrow R^- + RHg^\bullet \xrightarrow{Hg^o} RHg_n^\bullet$$

$$R^- + H^+ \longrightarrow RH$$

Alternatively, in some cases the formation of RHgX by reaction between polarised mercury and RX has been postulated, followed by subsequent reduction.[14,41]

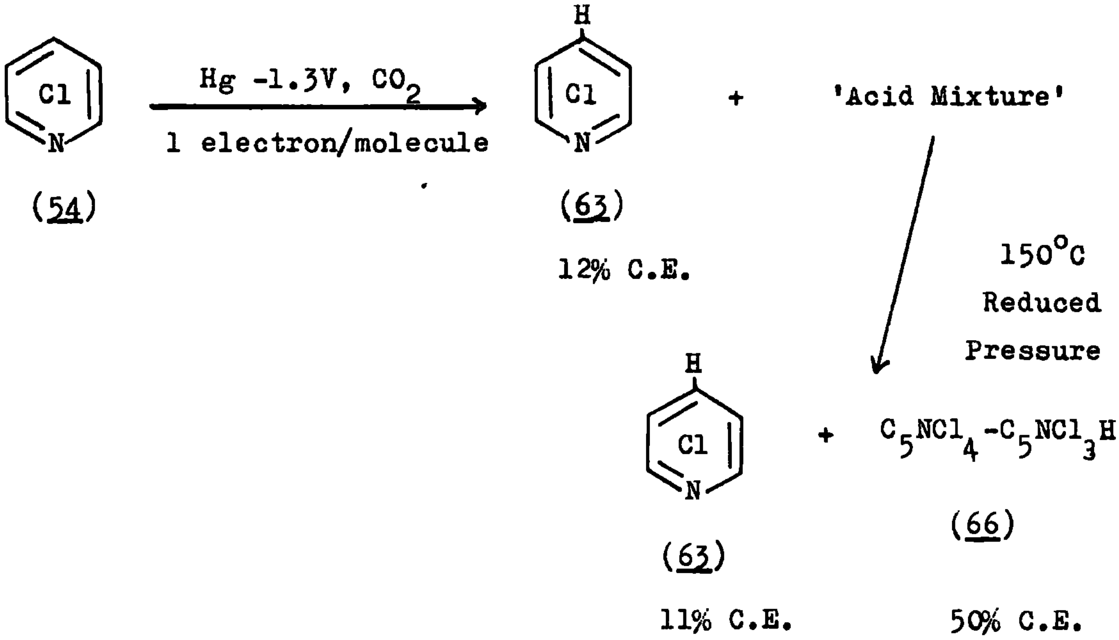
An attempt to reduce pentachloropyridine (54) on a lead cathode was made difficult by the formation of a film on the electrode surface, stopping the current. After passage of 0.87 electrons/molecule (63) was obtained with only a 15% current efficiency. A small yield of octachloro-4,4'-bipyridyl (65) was also obtained (9% C.E.). This was identical with an authentic sample derived from the chlorination of 4,4'-bipyridyl with phosphorus pentachloride. No organo-lead compounds were isolated and the cathode decreased only slightly in weight. A large amount of intractible material was obtained.

The reduction of (54) on a platinum cathode gave similar problems to lead but a current efficiency of 37% was obtained for the production of (63) after passage of 0.99 electrons/molecule.

Using all three cathode materials the reductions produced a purple colouration. This could not have been due to a stable radical anion from (65) as very little was produced and its reduction was later found to be completely irreversible.

2. Trapping Experiments with Carbon Dioxide

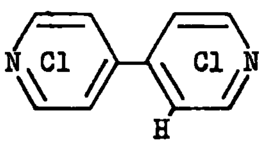
(a) Pentachloropyridine (54)



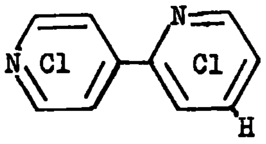
The reduction of (54) in D.M.F. saturated with carbon dioxide proceeded without any colour formation. There was competition between trapping with carbon dioxide and formation of (63). The trapping led, after acidification and extraction of involatile, water soluble material, to an acidic mixture from which no pure component could be separated. This decarboxylated in the mass spectrometer and showed parent peaks due to (63) and (66). It was readily decarboxylated by heating to 150°C under reduced pressure,and fractional sublimation then gave pure samples of (63) and (66).

Compound (63) analysed correctly for a tetrachloropyridine and its melting point agreed with the literature value for the 4-H isomer.[83] Its ^{1}H n.m.r. spectrum showed a singlet at δ 7.86, compared to published values of 7.90, 7.41 and 8.35 for the 4-H, 3-H and 2-H isomers respectively.[81]

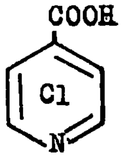
Compound (66) had the correct elemental analysis for a heptachlorobipyridyl. Its ^{1}H n.m.r. spectrum showed a singlet at 7.08 ppm, compared to a published value of 7.10 ppm for 3-H-heptachloro-4,4'-bypyridyl (66a), and its melting point was also consistent with this compound.[84]



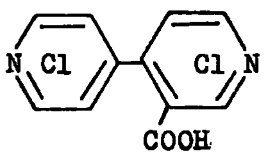
(66a)



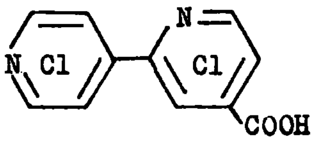
(66b)



(67)

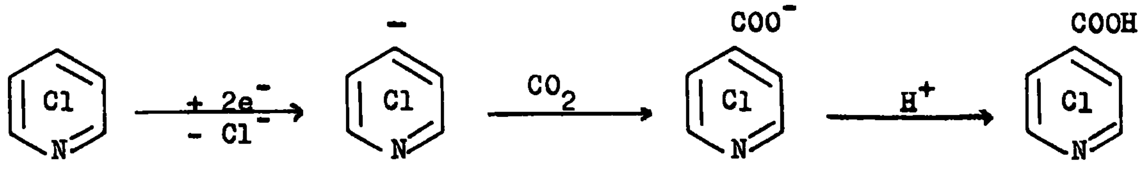


(68a)



(68b)

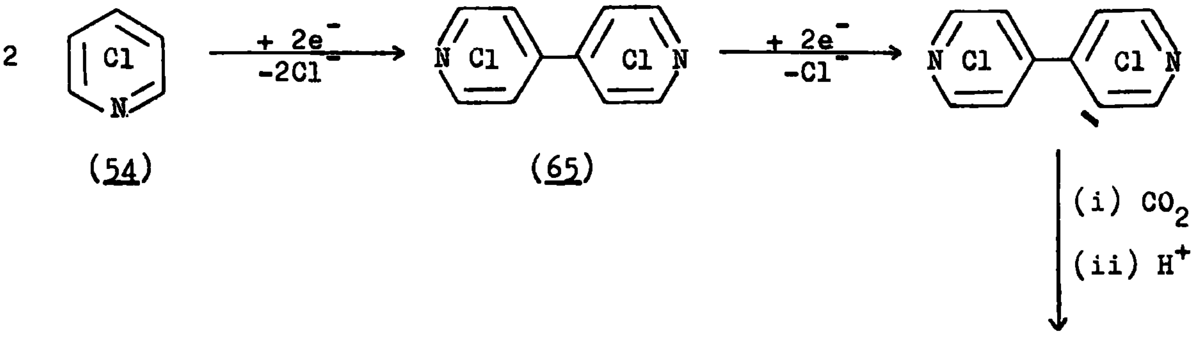
The products of the decarboxylation, (63) and (66), must have been derived from the corresponding acids (67) and (68). In view of the inability to produce acids by trapping the radical anions of the fluorinated compounds described earlier, and also the results obtained from (54) in the absence of carbon dioxide, it seems reasonable to suppose that these acids are formed from the corresponding carbanions. Thus (67) would be formed via the route:



(54) (69) (70) (67)

Additional evidence was provided when the catholyte from one reaction was heated and decarboxylation occurred. The same purple colour was produced as was observed during reduction in the absence of carbon dioxide, and it is known that decarboxylation of carboxylic acids produces carbanionic intermediates. Such a colouration is more commonly associated with paramagnetic species, and carbanions such as (69) would not normally be expected to be very stable. It may be that the presence of the tetraethylammonium counter-ion serves to stabilize it to a significant extent, and this effect may be worthy of further investigation.

The production of (68) is unexpected. The evidence available suggests that its decarboxylation product has the structure (66a), and thus the acid is (68a). This would be formed via coupling of (54) to (65), followed by further reduction and trapping with carbon dioxide:



(54) (65) (68a)

Only a trace of (65) was produced, however, in the absence of carbon dioxide, whereas (68) is the major product in its presence. This is clearly a contradiction. An alternative route to (68) would be nucleophilic attack by the carbanion (69) on the carboxylate anion (70) but this would give an acid of a different structure. This would probably be (68b), as it is known that the acid (67) undergoes nucleophilic attack at the 2-position.[85] Both routes require 4 electrons per molecule of (68) produced and the current efficiency was calculated accordingly.

When 1.90 electrons/molecule were passed, the yield of (67) increased to an 18% C.E., and that of (68) dropped to 35%. This is consistent with the fact that formation of (68) requires two molecules of (54), and will therefore slow down as (54) is consumed and its concentration decreases.

The two reactions described were the only ones performed in a larger cell than normal. When the normal smaller cell was used the amount of (63) formed directly, without trapping by carbon dioxide, fell drastically to a yield of only 2% C.E. after passage of 1.12 electrons/molecule. This probably means that the circulation of the carbon dioxide in the large cell was inefficient, and in fact trapping with carbon dioxide is a much more favourable reaction than protonation to give (63).

(b) Octachloro-4,4'-bipyridyl (65)

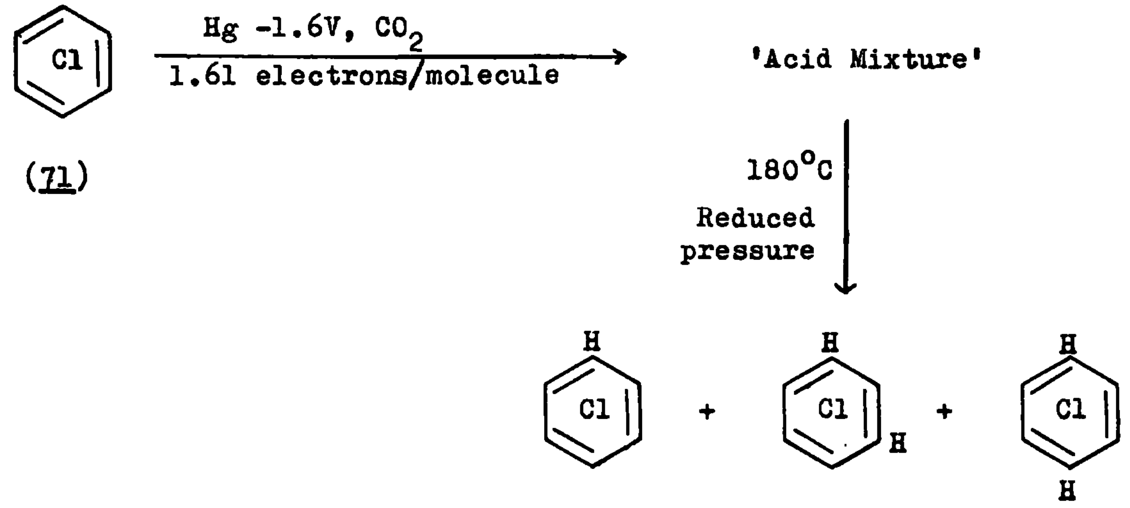
To try and determine definitely the route to the heptachlorobipyridyl carboxylic acid (68) obtained above, octachloro-4,4'-bipyridyl was reduced under identical conditions, to see if the product was the same. The result, however, was not conclusive.

The problem is the basic insolubility of (65) in D.M.F., which meant that only a small part of the substrate added to the catholyte was in solution. The reduction potential used was the same as for pentachloropyridine (54), i.e. -1.3V, in order to get a reasonable current, although it was later found by voltammetry that it reduces more readily. After passage of 1.51 electrons/molecule only a very small amount of acid mixture was obtained. This could not be decarboxylated by heating to 160°C under reduced pressure but sublimed at this temperature under vacuum. It decarboxylated in the mass spectrometer, however, and showed peaks at $^{m}/e$ 360 and 394 due to hexa- and heptachlorobipyridyls. The former was by far the larger, showing that the major product was the doubly reduced compound. It seems unlikely, therefore, that this reduction can be the source of the high yield of heptachlorobipyridyl carboxylic acid (68) obtained from pentachloropyridine (54). The fact that the melting-point and ^1H n.m.r. spectrum of the heptachlorobipyridyl (66) agrees with that of (66a) may be coincidental, as the production of (66a) could not be explained on the basis of the above observations.

(c) Hexachlorobenzene (71)

In order to determine whether trapping with carbon dioxide was generally applicable to aromatic chlorocarbons, it was next applied to hexachlorobenzene (71).

Hexachlorobenzene poses the same problem of insolubility as the bipyridyl (65). Consequently, it was found that the reduction potential of -1.6V necessary to achieve a reasonable current caused more than a single reduction step to take place.



(71) (72) (73) (74)

	(72)	(73)	(74)
Current Efficiency	20%	21%	
^1H n.m.r. shift v. internal T.M.S.	7.46ppm	7.32ppm	7.47ppm
Literature value[86]	7.53ppm	7.38ppm[a]	7.54ppm

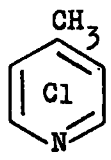
a : predicted value

The acidic mixture obtained after acidification of water soluble products required a higher temperature for decarboxylation than that obtained from pentachloropyridine. G.l.c. with mass spectroscopy showed the product to be a mixture of pentachlorobenzene (72) and tetrachlorobenzene. The ^{1}H n.m.r. spectrum of the mixture showed the presence of two tetrachlorobenzenes, inseparable by g.l.c., in the ratio of approximately 1:1. These were identified as (73) and (74) by comparison with literature values.[86] The value for (73) was a predicted shift as no experimental value appears in the literature. The error between the observed and literature values is 0.06 to 0.07ppm for all three products.

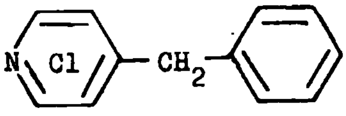
Thus, reduction of the anion of pentachlorobenzoic acid results in replacement of the meta or para chlorine atoms. No evidence of ortho reduction was seen. In the reduction of pentachlorobenzene (71), ortho, meta and para dihydro-compounds are produced in the ratio 14:65:21.[54] i.e. meta reduction is much preferred.

3. Trapping Experiments with Alkyl Halides

A suitable method of trapping carbanions is by nucleophilic attack on a susceptible species, such as an alkyl halide. Iodide is readily displaced from iodomethane by nucleophiles. When pentachloropyridine (54) was reduced at -1.2V in the presence of iodomethane, which is not itself reducible at this potential, no purple colouration was observed but, instead, an orange colour was produced. A large amount of iodide was displaced and precipitated as tetraethylammonium iodide. Some mercuric iodide was also obtained. A lot of material was lost in this reaction, but there was evidence for the presence of some of the trapped product (75) from g.l.c. with mass spectroscopy on the reaction mixture. There appeared



(75)



(76)

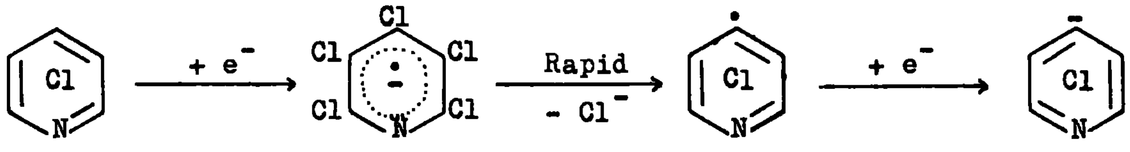
to be less of (75), however, than of the tetrachloropyridine (63), but it might be possible to improve this reaction and obtain a better yield of (75).

Benzyl chloride did not appear to have any effect on the reduction of (54), the normal purple colour being formed in its presence. Passage of 1.06 electrons/molecule gave (63), with a current efficiency of 34%. The possible product of trapping (76) would be rather involatile and some may have been present in the involatile residue, which showed aromatic C-H stretching vibrations in its infra-red spectrum. It was not possible to get anything out of this, however.

4. Voltammetry

(a) Pentachloropyridine (54)

Pentachloropyridine (54) was investigated jointly with Dr.O.R.Brown's group at Newcastle University. The solution used was 4mM in (54) and 0.1M in tetraethylammonium fluoroborate in D.M.F. As observed with the fluorinated pyridines, the $Ep_{\frac{1}{2}}$ varied with sweep rate, being -1.25V at 10mV/sec and -1.32V at 1V/sec. No reversibility of the reduction wave could be seen and this wave corresponded to a two-electron reduction. A complex theoretical analysis of the wave shape showed that a rapid irreversible process occurs after the first electron transfer.[87] This is most probably loss of Cl^-, so that the electrode reaction is:



(54) (69)

This supports the view that products derived from protonation and trapping with carbon dioxide are most probably formed from the carbanion (69).

On the reverse sweep a small oxidation wave was observed at $Ep^a \simeq -0.60V$, with a corresponding reduction wave visible on the second sweep at $Ep^c \simeq -0.70V$. This only appeared on a mercury cathode and not on gold or platinum. This was explained by the reversible oxidation of a radical adsorbed on the mercury surface:

$$R^\bullet \xrightarrow{Hg} RHg^\bullet_{(ads)} \rightleftharpoons e^- + RHg^+$$

On sweeping past the first reduction peak, a series of waves at more negative potentials could be seen, probably due to step-wise replacement of chlorine by hydrogen.

The voltammogram of (54) was also run on the Electroscan instrument used previously. The $Ep_{\frac{1}{2}}$ recorded at a 20mV/sec sweep rate was -1.42V, demonstrating the need to record voltammograms under identical conditions when comparing the $Ep_{\frac{1}{2}}$'s of different compounds.

(b) Octachloro-4,4'-bipyridyl (65)

Octachloro-4,4'-bipyridyl (65) was investigated on the Electroscan instrument. Unlike the corresponding fluorinated compound (56) it showed no sign of reversibility or colour formation at sweep rates up to 100mV/sec. The $Ep_{\frac{1}{2}}$ measured at 20mV/sec was -1.18V, but it varied between -1.17V at 10mV/sec and -1.21V at 100mV/sec. A series of subsequent reduction waves could again be seen at more negative potentials, the first with an $Ep_{\frac{1}{2}}$ of -1.40V at 20mV/sec sweep rate. Thus, both of the first two reduction processes can take place when (65) is reduced at the same potential as required for (54), which agrees with the result of the trapping experiment on (65) with carbon dioxide, (see p.48).

The difference between the behaviour of (65) and that of octafluoro-4,4'-bipyridyl (56), which has a stable radical anion, is interesting. It may well be that the negative charge in the radical anion of (65) cannot be stabilised by conjugation between the two rings because the bulky chlorine substituents prevent them from becoming coplanar.

To obtain some evidence on the conjugation between the rings, the ultra-violet spectrum of (<u>65</u>) was compared with that of 4-H-tetrachloropyridine (<u>63</u>), which shows absorptions in cyclohexane solution at 233nm (ε 12,600) and 292nm (ε 6,700). The bipyridyl (<u>65</u>) has absorptions at 236nm (ε 23,400) and 300nm (ε 11,800). The conclusion is that there is no evidence for any conjugation, as there is a negligable shift in the wavelengths, and the intensity is only doubled due to the presence of two pyridine rings in the molecule. The heptachlorobipyridyl (<u>66</u>) gave a similar spectrum with absorptions at 232nm (ε 22,600) and 294nm (ε 10,200).

CHAPTER IV

ELECTROCHEMICAL REDUCTION OF PERFLUORO-OLEFINS

IV.A INTRODUCTION

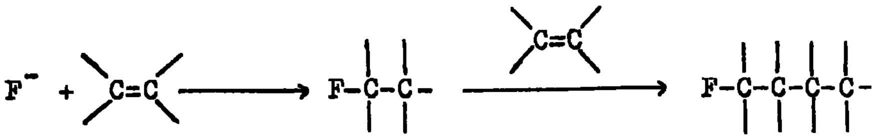
As was described in Chapter II, the reduction of compounds containing two halogen atoms on adjacent carbon atoms generally leads to displacement of both, probably in a concerted process, resulting in an increase in the unsaturation of the molecule. Thus 1,2-dihaloalkanes give olefins and 1,2-dihaloalkenes give acetylenes, (p.18). This type of reduction has been applied to perfluorinated systems in the conversion of fluorinated cyclohexadienes to aromatic compounds, (p.23).

In the work described here a brief survey was performed on the simple fluoro-olefins : hexafluoropropene (44); octafluorobut-2-ene (77); and tetrafluoroethylene (22). It was hoped that generation of their radical anions might lead to some interesting reactions.

As might be expected, the reductions resulted in loss of fluoride ion from these olefins, and this is known to induce oligomerisation of fluoro-olefins.[76] Products from this type of reaction were found, so for greater clarity in the later discussion, fluoride-ion-induced oligomerisation is outlined briefly here.

1. Fluoride-Ion-Induced Oligomerisation of Fluoro-olefins

Fluoro-olefins are very susceptible to nucleophilic attack and consequently attack by fluoride ion generates a carbanion (78), which can lead to dimers and other oligomers by attack on an olefin molecule.



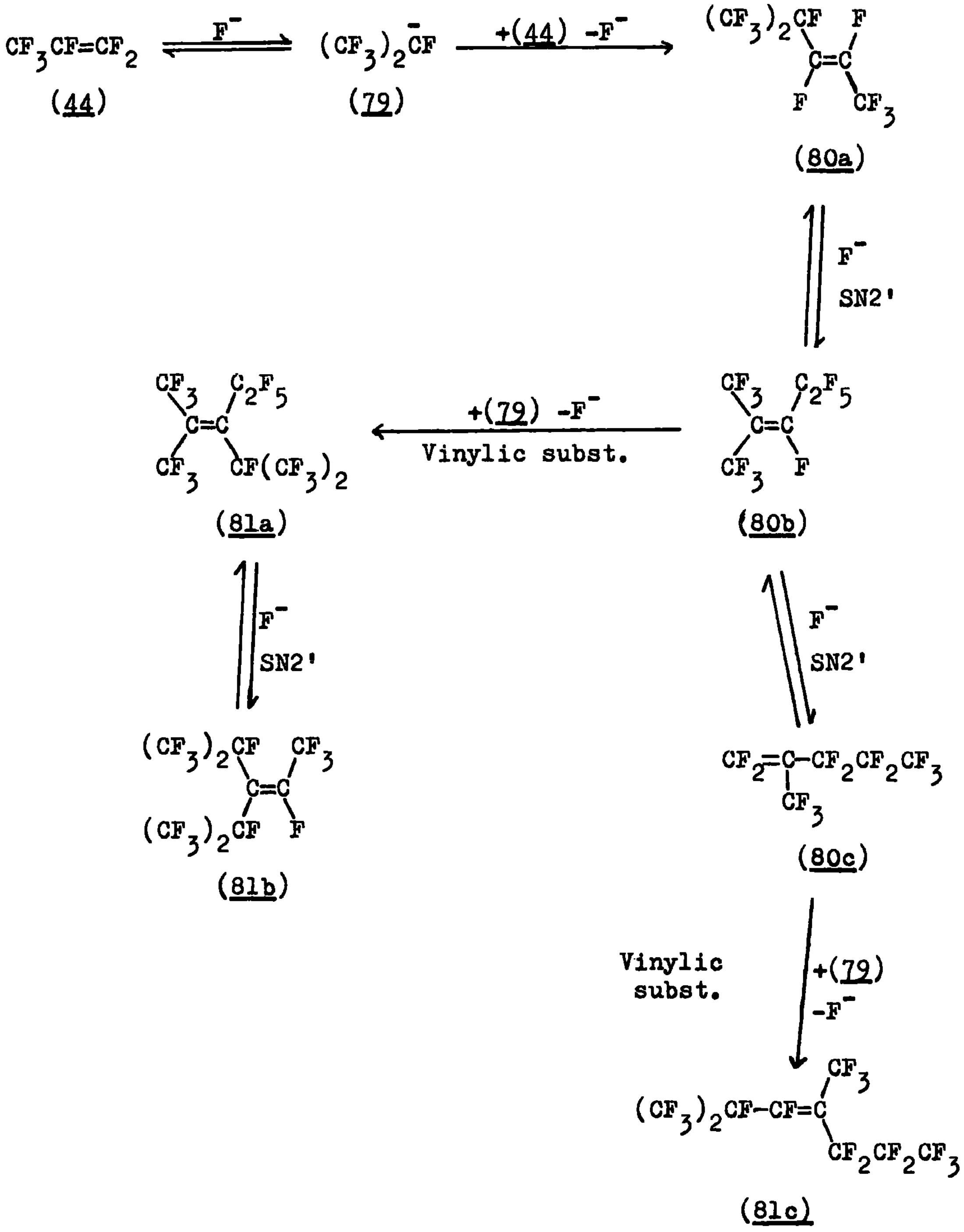
(78)

Elimination of fluoride ion or abstraction of a proton by the intermediates normally prevents the formation of polymers.

(a) Hexafluoropropene

The oligomerisation of hexafluoropropene (44) is shown in Scheme IV.1.

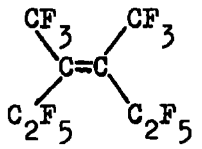
Scheme IV.1



Reactions in polar, aprotic solvents at room temperature give two dimers (80a) and (80b), and two trimers (81a) and (81b).[88] Dimer (80a) and trimers (81a) and (81b) are the products of kinetic control. Dimer (80b) is a product of thermodynamic control and the other dimer can be converted into it under more vigorous conditions by an SN2' reaction with fluoride ion. At higher temperatures a third trimer (81c) is produced, which is a product of thermodynamic control. This is thought to be formed by attack of the heptafluoroisopropyl anion (79) on the terminally unsaturated dimer (80c), although none of this has been isolated. The two kinetic trimers (81a) and (81b) can be converted into (81c) under more vigorous conditions. Thus, the actual yields of the various dimers and trimers isolated depends greatly on the reaction conditions.

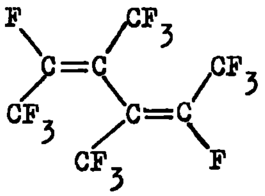
(b) Octafluorobut-2-ene

The oligomerisation of octafluorobut-2-ene (77) occurs less readily than hexafluoropropene. After heating in a sealed nickel tube with caesium fluoride and sulpholane for 24 hours at 130°C, the conversion is only 44%.[89] The major product is a mixture of cis and trans isomers of the dimer C_8F_{16} (82) (69% yield). In addition, various defluorinated

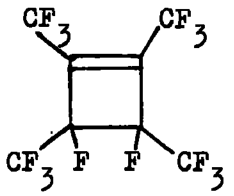


+ trans

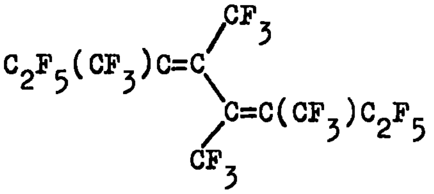
(82)



(83a)



(83b)



(84)

products are obtained. Two isomers of C_8F_{14}, (83a) and (83b), are produced in a total yield of 11.5%, with a 15.5% yield of $C_{12}F_{22}$ (84). These were originally thought to be formed by reaction with the nickel walls of the reaction vessel, but defluorination also occurs when the reaction is performed in glass apparatus at atmospheric pressure, using tetraglyme as the solvent.[90] At 92°C a 49% yield of the dimers (82) is obtained, together with the defluorinated compounds (84) and $C_{12}F_{20}$ (85).

The defluorination mechanism favoured by the authors was via formation of complex salts like $Cs^+F_3^-$. A mechanism involving nucleophilic attack on a fluorine atom of (77) by an intermediate carbanion was considered less likely. Another alternative mechanism that has been suggested[91] is an electron transfer process of the type:

$$R_F^- + C_nF_{2n} \longrightarrow R_F^\bullet + C_nF_{2n}^{\bar{\bullet}} \xrightarrow[(ii)\ -\ F^-]{(i)\ -\ F^\bullet} C_nF_{2n-2}$$

(c) Tetrafluoroethylene

The oligomerisation of tetrafluoroethylene (22) also requires more vigorous conditions than hexafluoropropene. The products formed are highly branched, internally unsaturated compounds, with a general formula $(C_2F_4)_n$, where n = 4,5,6 or 7.[92,93] With a variety of solvents and fluoride ion sources at 100°C and a pressure of (22) of 10 to 20 p.s.i. the major product is the pentamer, $C_{10}F_{20}$. Increasing the pressure results in an increase in the amount of heptamer, $C_{14}F_{28}$, at the expense of the pentamer. The yield of oligomers in these reactions is normally less than 70%, due to side reactions between the highly reactive pentafluoroethyl anion and the solvent.

IV.B ELECTROCHEMICAL REDUCTION OF HEXAFLUOROPROPENE

In the present work the reductions were performed by bubbling the gaseous hexafluoropropene (44) continuously through the cathode compartment of the cell during the electrolysis, so as to maintain a saturated solution throughout. The gas was recycled around a closed system by means of a peristaltic pump, and two ice/salt traps on the outlet from the cell prevented volatile liquid products from circulating with it. The experimental techniques are described fully in Chapter VII.

In view of the fact that this was only a preliminary survey, the circulating system was only a temporary arrangement and did not allow for quantitative recovery of unreacted (<u>44</u>). The amount of reaction expected was, therefore, calculated from the amount of charge passed, which was known accurately.

1. Reduction in Anhydrous D.M.F.

$$\underset{(\underline{44})}{C_3F_6} \xrightarrow[\text{2 electrons/molecule to 1.16g}]{\text{Hg -1.9V, 0.0155 Faradays}}$$

Volatile liquid	(1.26g)
High-boiling oil	(0.81g)
Intractible residue	(0.89g)
Total	2.96g

When hexafluoropropene (<u>44</u>) was reduced at -1.9V on a mercury cathode in anhydrous D.M.F., the catholyte started to turn yellow and cloudy immediately. The colour darkened during the electrolysis, and was finally brown. Enough charge was passed to perform a two-electron reduction on only 1.16g of (<u>44</u>) and yet the recovered products amounted to 2.96g.

A volatile liquid was recovered from the ice/salt traps and more was obtained after the volatiles from the catholyte had been transferred under vacuum into a cold trap, when it separated as a D.M.F.-insoluble lower layer.

Extraction of the involatile part of the reaction mixture, followed by molecular distillation under reduced pressure gave a high boiling point oil and an intractible residue.

(a) Volatile Products

The volatile liquid was shown by g.l.c./mass spectroscopy to contain mainly dimers (30%) and trimers (69%) of hexafluoropropene (44). The dimers showed only one peak on g.l.c., but this was separated by preparative g.l.c. and its ^{19}F n.m.r. spectrum showed it to be a mixture of the dimers (80a) and (80b), which are produced by fluoride-ion-induced oligomerisation of (44),(see p.55). Three trimers were visible by g.l.c., in the ratio 9 : 32 : 59, and the two largest peaks had identical retention times with the trimers (81a) and (81b) obtained by fluoride ion reaction at room temperature. In view of the fact that no check had been made on the temperature during the electrolysis, it was assumed that the third trimer was (81c), obtained by fluoride ion reaction at elevated temperatures.

The mixture contained two minor components, both under 1%. The first was identified as $C_6F_{13}H$ (86), probably formed by protonation of an intermediate carbanion in a fluoride ion reaction; the second appeared to be $C_{12}F_{20}$ (85a).

G.l.c./mass spectroscopy on the D.M.F. showed that it also contained a small amount of (86) and also some C_3F_7H (87), formed by protonation of the carbanion (79) derived from hexafluoropropene.

With the exception of the defluorinated compound (85a), all of these products can be easily explained by fluoride-ion-induced oligomerisation of (44), the fluoride ion being liberated during the electrochemical step. Compound (85a) has had two extra degrees of unsaturation introduced, which could have occurred electrochemically. Defluorination has been observed in the fluoride-ion-induced oligomerisation of octafluorobut-2-ene, however, which also gives a compound of the same molecular formula, (see p.56). Therefore, the same type of process cannot be ruled out here. It appears that the defluorination steps must occur at an early stage on the route to (85a), as no $C_{12}F_{22}$ or $C_{12}F_{24}$ compounds are observed.

(b) Involatile Products

The high boiling yellow oil was shown by g.l.c. at high temperature to be a multicomponent mixture. Its infra-red spectrum showed C-H stretching vibrations, and its elemental analysis showed it to contain only 48.8% fluorine, (cf. C_3F_6 oligomers: 75.9%). Therefore, the solvent or electrolyte must somehow have been involved in its formation. Carbanions formed during fluoride-ion-induced reactions do not normally react with the solvent, except for the highly reactive pentafluoroethyl anion. It seems reasonable to assume, therefore, that the oil is formed by reaction of electrochemically generated species. The intractible residue may be derived similarly. It would be a rather fruitless exercise to speculate on the mechanism of these reactions without any knowledge of the structure of the products.

(c) Use of Current as an Initiator

To demonstrate that the current was only an initiator in the formation of the oligomers by liberating fluoride ion, a reaction was performed in which only enough charge was passed to perform a two-electron reduction on 0.30g of hexafluoropropene (44). The gas was then circulated for a further 8 hours with no current flowing. This gave an increased yield of oligomers from less charge. A total of 3.15g of the mixture was obtained containing:

C_6F_{12}	$C_6F_{13}H$	C_9F_{18}	$C_{12}F_{20}$
(80)	(86)	(81)	(85a)
40%	5%	47%	8%

Only two trimers (81a) and (81b) were formed and not the third 'thermodynamic' trimer (81c). This can be explained by the fact that only a small amount of charge was passed and not enough to raise the temperature greatly to favour production of (81c).

It is interesting that the yield of the defluorinated compound (85a) was increased. This cannot, therefore, be produced electrochemically. The defluorination occurring during the oligomerisation of octafluorobut-2-ene was suggested to occur via the formation of complex salts such as $Cs^+F_3^-$.[90] This would be unlikely in this case, where the fluoride ion is generated in situ and the counter ion present is Et_4N^+. One of the other suggested mechanisms may, therefore, be operating, (see p.57).

In this reaction the amount of the involatile products was greatly decreased, demonstrating that these are formed by the electrochemical process.

A rather unlikely possibility, that the fluoride ion was not produced electrochemically, but by dissociation of the tetrafluoroborate anion (88), was eliminated when a control experiment with no current passed produced no oligomers.

$$\underset{(88)}{BF_4^-} \rightleftharpoons \underset{(89)}{BF_3} + F^-$$

(d) Reduction in the Presence of Boron Trifluoride

An attempt to eliminate fluoride-ion-induced reactions by performing the reduction in the presence of boron trifluoride (89) to 'mop up' any fluoride ion produced, by the equilibrium above, proved unsuccessful, as the boron trifluoride diethyl etherate used was itself reducible at -1.9V. This reaction finally yielded a volatile fluorocarbon mixture, similar to that obtained previously, and a large amount of tar.

(e) Reduction on a Carbon Cathode

Hexafluoropropene (44) was also reduced in an undivided cell, with a porous carbon cathode, through which the gas could be bubbled into the cell. Only enough charge was passed to produce a two-electron reduction of 0.68g of (44) and 1.98g of oligomers was obtained. In addition, the D.M.F. yielded 1.5g of the gaseous product C_3F_7H (87), observed only in traces previously. This was identified as 2-H-heptafluoropropane by its ^1H and ^{19}F n.m.r. spectra.[94] This is the expected product arising from protonation of the intermediate heptafluoroisopropyl anion (79). This was thought to be formed because the cell was undivided and acidic species formed at the anode could then protonate (79),which was confirmed by dividing the cell into two compartments and using the same carbon cathode, when the products were the same as obtained on mercury.

It is interesting to compare the amount of the protonated products (86) and (87) formed in the undivided cell with the amount of charge passed. If the electrochemical step produces one fluoride ion for each electron, then in this reduction 0.0099 moles of fluoride ion were produced. A total of approximately 0.01 moles of (86) and (87) was produced, which is excellent agreement. It appears that all of the fluoride ion produced had been used in formation of (86) and (87).

2. Reduction in Aqueous D.M.F.

When hexafluoropropene (44) was reduced in D.M.F. containing 2½% water by volume, no oligomers of (44) were produced but the anion (79) was protonated to give C_3F_7H (87). Again there was close agreement between the 0.0119 moles of fluoride ion theoretically liberated electrochemically and the 0.0116 moles of (87) isolated.

It is interesting that (87) is formed at all in the presence of water, as this greatly deactivates fluoride ion by solvation and inhibits its addition to fluoro-olefins. A possible explanation is that the F^-, which is formed at the cathode in the so-called 'double layer', adds immediately to a molecule of (44) which is also in the layer, before coming into contact with the bulk solution and being solvated.

IV.C ELECTROCHEMICAL REDUCTION OF OCTAFLUOROBUT-2-ENE

The reduction of octafluorobut-2-ene (77) was similar to that of hexafluoropropene (44), giving products derived from fluoride-ion-induced oligomerisation. It is less susceptible to this type of reaction than (44) and gave a correspondingly lower yield of oligomers. Passage of enough charge to perform a two-electron reduction on 2.26g of (77) gave only 0.96g of a volatile mixture containing:

C_8F_{14}	C_8F_{16}	$C_{12}F_{22}$
(83)	(82)	(84)
12%	80%	8%

The dimer (82) had an identical g.l.c. retention time and mass spectrum to the mixture of cis and trans isomers obtained by fluoride ion reaction, (see p.56). The defluorinated products (83) and (84) are probably also products of the fluoride-ion-induced reaction.

The products of the electrochemical process were again a high boiling point multicomponent oil, incorporating the solvent, and an intractible residue.

IV.D ELECTROCHEMICAL REDUCTION OF TETRAFLUOROETHYLENE

The reduction of tetrafluoroethylene (22) gave no oligomers, as might be expected from the fact that the fluoride-ion-induced oligomerisation of (22) requires elevated temperatures and pressures. Passage of enough charge to perform a two-electron reduction on 0.67g of (22) gave 0.53g of intractible, involatile residue. A trace of a more volatile component was obtained but this could not be identified. Its mass spectral parent peak was at 459, which could not easily be explained by just carbon, fluorine and hydrogen. Possibly this had been formed by reaction with the solvent.

When (22) was reduced in aqueous D.M.F. the major product was pentafluoroethane, C_2F_5H (90), showing that the pentafluoroethyl anion is produced and hence that fluoride ion must be eliminated during the reduction of (22). Compound (90) was identified from its mass spectrum and by comparison of its infra-red spectrum with that in the literature.[95] A small amount of another, unidentified component was also present.

IV.E CONCLUSION

Electrochemical reduction of the fluoro-olefins studied liberates fluoride ion, which then causes oligomerisation of hexafluoropropene (44) and octafluorobut-2-ene (77). The amount of the intermediate carbanions from (44) trapped by protonation suggests that each electron generates one fluoride ion. This is in agreement with a concerted two-electron elimination of two halide ions, which is normally observed with 1,2-dihalo compounds. This would result in the formation of the acetylene (91) or the allene (92) from (44), but there is no direct evidence for their production. In fact the electrochemical process leads to high boiling oils and tars, and does not appear to be useful.

$CF_3C\equiv CF$ (91)

$CF_2=C=CF_2$ (92)

The generation of fluoride ion in solution by this method might be useful. Active fluoride ion is generally obtained in solution in aprotic solvents from an alkali metal salt but this is limited by their solubility. A lot of work has gone into obtaining free fluoride ion by using crown ethers, which complex with the counter ion and increase the solubility.[96] The oligomerisation of (44) induced by fluoride ion generated free in solution electrochemically occurred quite efficiently, considering the crudeness of the apparatus. Any wider application of this was not investigated, however, as the aim of the project was to investigate the electrochemical reactions, which were unproductive.

CHAPTER V

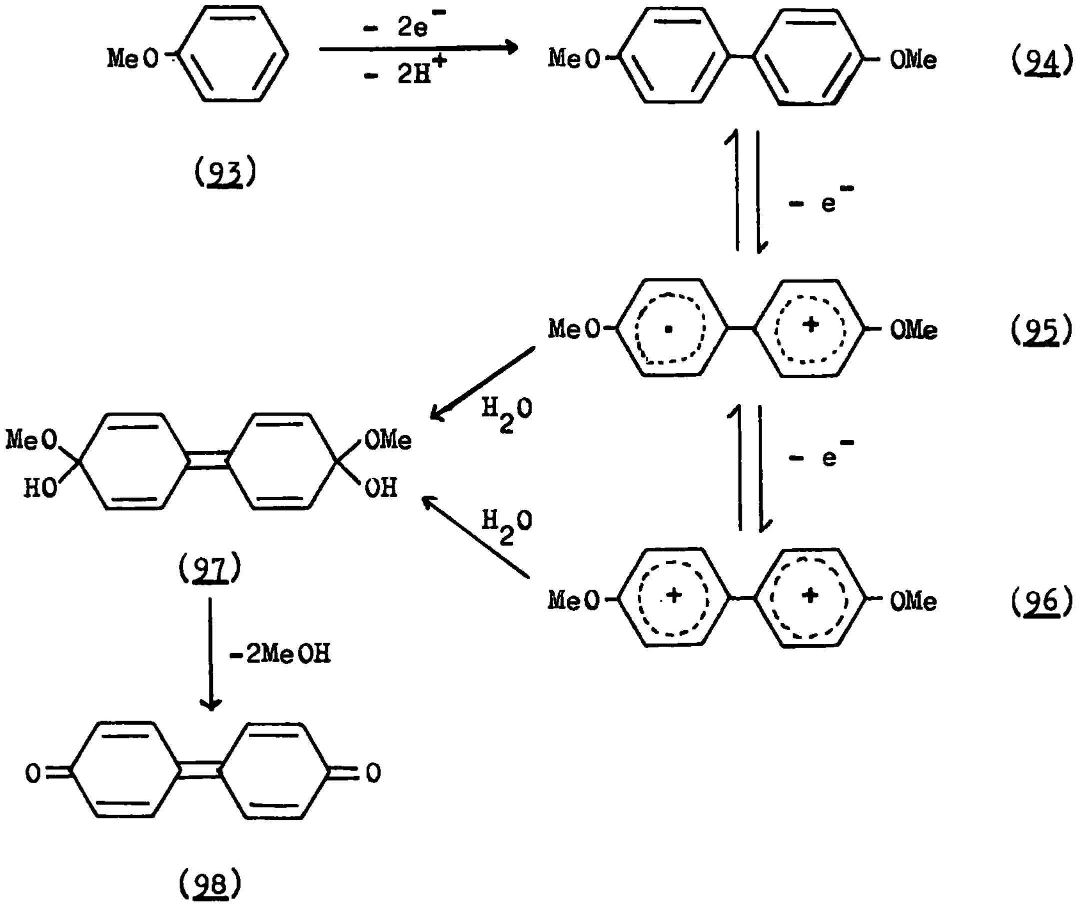
ELECTROCHEMICAL OXIDATION OF POLYFLUOROANISOLES

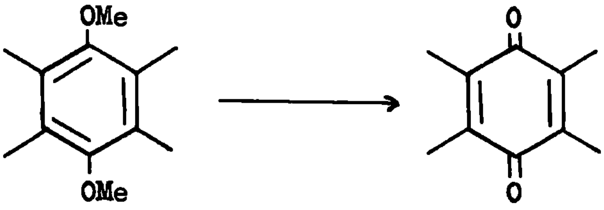
V.A INTRODUCTION

The electrochemical oxidation of aromatic compounds is a subject which has received extensive coverage. (See, for example, the relevant chapters in references 1, 2 and 3.) Topics of particular relevance to the work on fluorinated anisoles described later are discussed here.

1. Anodic Oxidation of Aryl Methyl Ethers

The electrochemical oxidation of anisole (93) and simple derivatives gives coupling to the corresponding derivative of 4,4'-dimethoxybiphenyl (94).[97] Yields are generally low using conventional solvents such as acetonitrile, because the reaction is complicated by the fact that the product is invariably more easily oxidised than the anisole. Thus,





(99) (100)

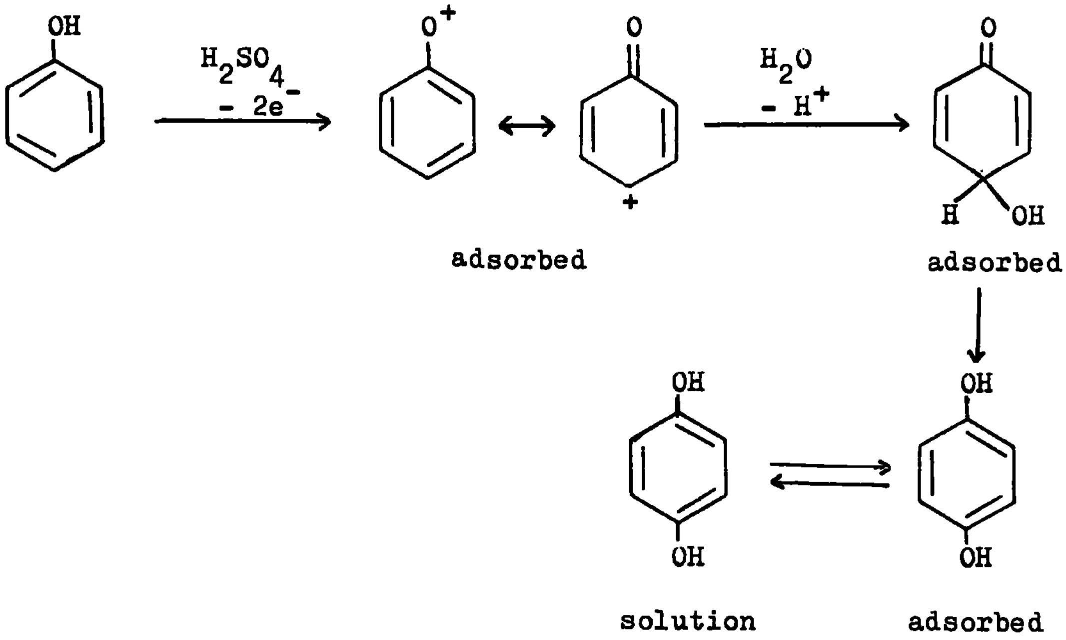
oxidation to the radical cation (95) and dication (96) can occur. These are highly reactive species, reacting with any nucleophiles present. In nominally non-aqueous solvents traces of water are normally present, even after the most rigorous purification.[98] Reaction with water will give (97), which may lose methanol to give the quinone (98). This type of reaction has been observed in the oxidation of (99) in acetonitrile, giving the quinone (100) in quantitative yield.[99] Alternatively, at high radical cation concentrations, polymerisation may occur.

It is possible to get reasonable yields of the coupled products by performing the oxidations in a solvent consisting of a mixture of methylene chloride and trifluoroacetic acid. In this highly acidic medium, in which the acid is an extremely weak nucleophile, the radical cation (95) of the dimer has a very long lifetime. It can be reduced back to (94) after the electrolysis, either electrochemically or with zinc dust. Good yields are only obtained, however, when dilute solutions are used and the reaction is only taken to low conversion.

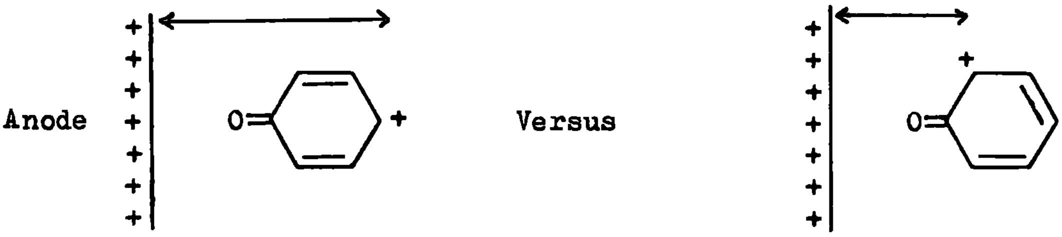
The mechanism favoured by the workers concerned involves dimerisation of the radical cation formed by one-electron oxidation of the anisole (93), followed by deprotonation.[100] An alternative mechanism which has much support is electrophilic attack by a radical cation on the substrate.[101,102]

It is interesting that, in simple anisole derivatives, coupling always occurs through the position para to the methoxy-group, whereas in electrophilic reactions it has an ortho/para directing influence. In fact no coupling is observed at all when the para position is blocked by a substituent other than hydrogen. It is possible that steric factors inhibit coupling ortho to the methoxy group but this is not observed in the acetoxylation reactions described later.

A similar orientation was observed in the oxidation, in sulphuric acid, of phenol to hydroquinone in over 90% yield,[103] for which the following mechanism was proposed:[104]



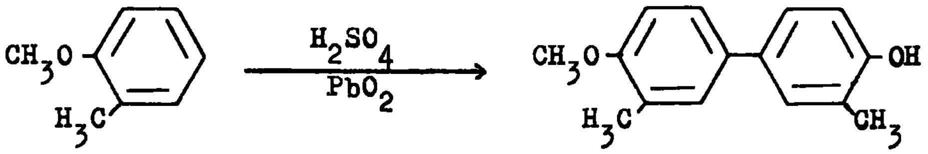
It was suggested that the high yield of the hydroquinone was due to the field effect of the anode, which tends to keep the positive charges as far apart as possible due to coulombic repulsion:



A similar effect might be operating for the anisoles, with the reactive intermediate again orientated with oxygen towards the anode and thus inhibiting reaction at the ortho position.

Oxidative coupling reactions can also be used for intra- or intermolecular coupling of molecules containing two methoxy-substituted aromatic rings in the same molecule.[100,105] In these reactions there is evidence for both the radical cation coupling mechanism and electrophilic attack on an unoxidised aromatic ring.

Demethylation has also been observed during oxidative coupling:[106]



2. Anodic Substitution Reactions of Aromatic Compounds

A much studied anodic process is the substitution reaction. The general expression for this is:

$$R\text{-}E + Nu^- \longrightarrow R\text{-}Nu + E^+ + 2e^-$$

E is often hydrogen, in which case the overall reaction is replacement of H^+ by a nucleophile, but it can be another atom or group e.g. t-butyl, OCH_3 or COO^-. A wide range of nucleophiles can be used, including H_2O, ROH, OH^-, RO^-, $RCOO^-$, NO_3^-, SCN^-, $SeCN^-$, CH_3CN, NO_2^-, N_3^-, OCN^-, pyridine, halide ion, and CN^-. The substitution can occur either in an aromatic ring or in an alkyl side-chain.

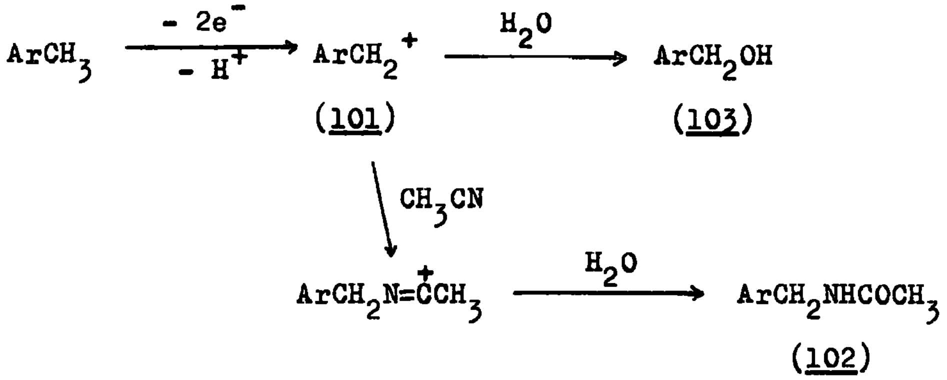
Anodic substitution can be divided into two types, indirect and direct processes. In an indirect process the anode merely serves as a source of a reactive species e.g. chlorine from chloride ion, or methoxy-radical from methoxide ion. This then attacks the organic substrate in the same way as if it had been generated chemically. In a direct process the organic substrate is oxidised to a radical cation or dication, which then reacts with the added nucleophile. In many cases not enough information is available to decide whether a direct or an indirect process is operating.

Two types of reaction of relevance to the work described later are those with acetonitrile (acetamidation) and carboxylic acids or their anions (acyloxylation). It is also difficult to prevent the hydroxylation reaction with water.

(a) Acetamidation

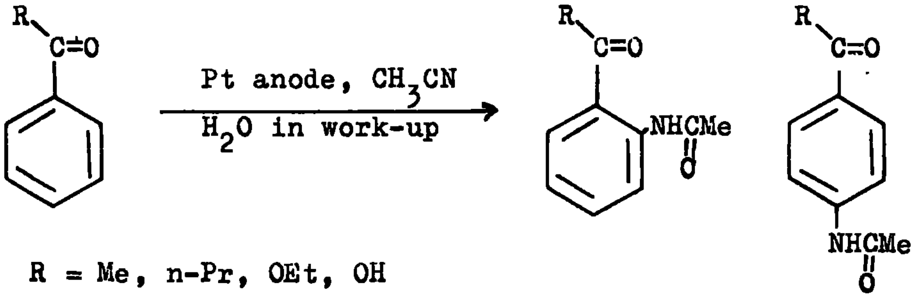
The acetamidation reaction generally gives N-alkylacetamides (102) by substitution in the side-chain (Scheme V.1). Only methyl substituted aromatics are good substrates for this reaction;[107] ethylbenzene and isopropylbenzene give other products predominantly.[108]

Scheme V.1



In order to avoid the hydroxylation reaction, giving (103), a carbon anode is preferable.[107] It has been found that by careful choice of the conditions, up to 95% of the N-alkylacetamide (102) can be obtained, even at water concentrations as high as 10%.[109] Thus the cation (101) is reacting with the weakest nucleophile in the system, acetonitrile.

Nuclear acetamidation is not common, but has been observed:[110]

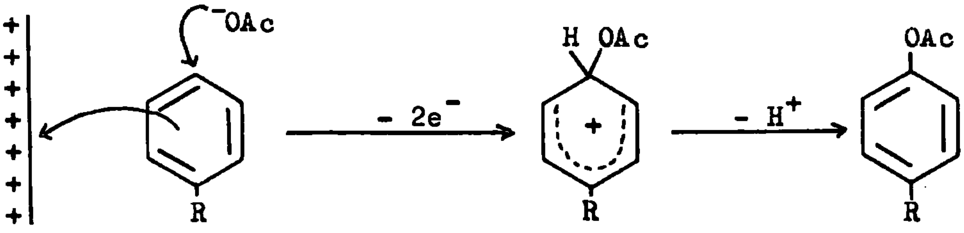


Only the ortho- and para-substituted products were obtained in this reaction.

(b) Acyloxylation

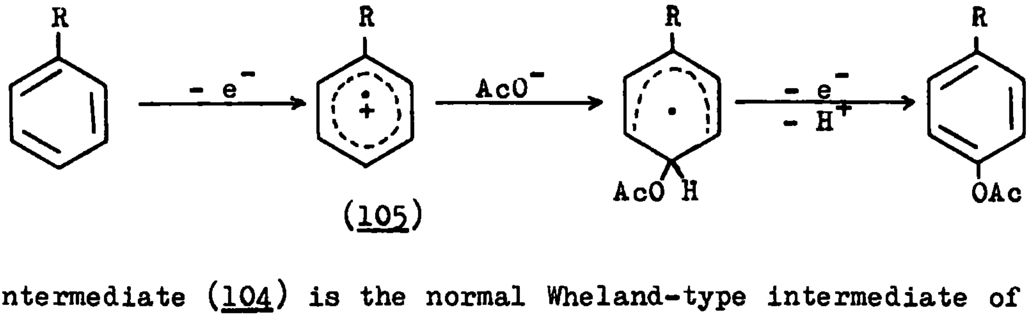
Substitution by an acyloxy group can be achieved by electrolysis in the presence of a carboxylate in a suitable solvent. The most common process is acetoxylation using acetic acid as solvent, with sodium acetate normally as the electrolyte. These are direct processes, occurring at the half-wave potential of the aromatic, well below the 2.0V necessary to oxidise acetate ion. Anisole, for example, can be acetoxylated at 1.5V.[111] It is found that nuclear acetoxylation requires the presence of acetate ion, whereas side-chain acetoxylation will occur using other electrolyes.[111]

This has been interpreted as a concerted acetate-ion-assisted two electron transfer from the aromatic to the anode in the former case, with simultaneous formation of a C-O bond:



(104)

It is possible that nuclear acetoxylation may involve attack of acetate ion on the radical cation (105), and that acetic acid is not a strong enough nucleophile to do this:[112]



(105)

The intermediate (104) is the normal Wheland-type intermediate of electrophilic substitution reactions and, if the former mechanism is correct, the isomer distribution of the acetoxylated products should be similar to that obtained in electrophilic reactions. A similarity has been observed for a number of mono-substituted benzenes.[111] Anisole, for example, gives the ortho, meta and para isomers in the ratio 67 : 4 : 29. There is also a reasonable correlation, however, between the isomer distribution and the calculated electron density in the radical cation.[113]

Anodic side-chain acetoxylation, occurring in the absence of acetate ion, was explained by a mechanism involving the cation (<u>101</u>):[111]

$$\begin{tikzcd}
\mathrm{ArCH_3} \arrow[r, "-\,e^-"] & {[\mathrm{ArCH_3}]^{+\cdot}} \arrow[r, "-\,H^+"] & \mathrm{ArCH_2^{\cdot}} \arrow[r, "-\,e^-"] & \mathrm{ArCH_2^+} \\
 & & & (\underline{101}) \arrow[d, "\begin{array}{l}\mathrm{HOAc}\\ -\,\mathrm{H^+}\end{array}"] \\
 & & & \mathrm{ArCH_2OAc}
\end{tikzcd}$$

An unusual reaction has been observed in the acetoxylation of 2- and 4-fluoroanisole in acetic acid/potassium acetate.[114] These give substitution of the fluorine atom to produce 2- and 4-acetoxyanisole respectively and only traces of the expected products formed by substitution of ring hydrogen. The 3-fluoro compound and also 4-bromo- and 4-chloroanisole give only the expected products. If 2- and 4-fluoroanisole were reacting by the conventional route, this would involve loss of F^+ at some stage, which is extremely unlikely. Loss of $F^{\cdot}$ was also ruled out for various reasons, leaving the authors with the conclusion that F^- is lost at some stage:

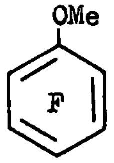
$$\begin{tikzcd}
\mathrm{ArF} \arrow[r, "-\,e^-"] & {[\mathrm{ArF}]^{+\cdot}} \arrow[r, "\mathrm{AcO^-}"] & {[\mathrm{FArOAc}]^{\cdot}} \arrow[r, "-\,e^-"] \arrow[d, "-\,F^-"] & {[\mathrm{FArOAc}]^{+}} \arrow[d, "-\,F^-"] \\
(\underline{106}) & & {[\mathrm{ArOAc}]^{+\cdot}} & {[\mathrm{ArOAc}]^{2+}} \\
 & & (\underline{107}) & (\underline{108})
\end{tikzcd}$$

The intermediates (107) or (108) would have to be reduced to the product by oxidation of the starting material (106).

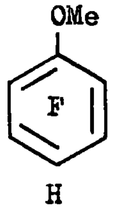
V.B OXIDATION OF POLYFLUOROANISOLES IN ACETONITRILE

The oxidations described here were performed in the two-compartment H-cell used previously, using acetonitrile as the solvent and tetraethylammonium fluoroborate as the electrolyte. This solvent/electrolyte system had an anodic limit of + 3.0V on the platinum anode used, relative to the S.C.E.

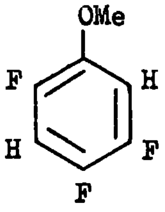
As was previously mentioned in Chapter II, the presence of electron-withdrawing halogen atoms makes oxidation more difficult and other workers have found that perfluoroaromatic compounds cannot be oxidised in conventional solvent systems. In agreement with these findings hexafluorobenzene could not be oxidised in the solvent used. Substitution of a fluorine atom by the electron-donating methoxy-group considerably decreased the oxidation potential, however, so that pentafluoroanisole (109), 2,3,5,6-tetrafluoroanisole (110), 2,4,5-trifluoroanisole (111), and 2,3,6-trifluoroanisole (112) could all be oxidised easily.



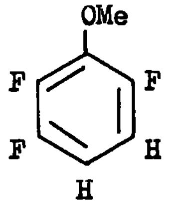
(109)



(110)



(111)

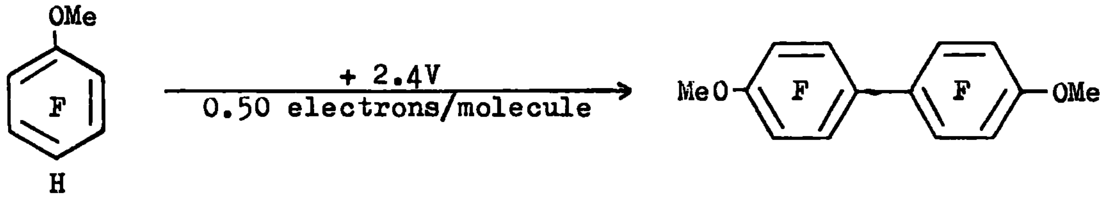


(112)

The oxidation of these species provides a possible route to some highly fluorinated radical cations, which have not previously been studied. Also, the presence of fluorine as a 'blocking' substituent greatly limits the possible follow-up reactions and so is also of relevance to the study of anisole derivatives in general.

1. Anisoles Containing Ring Hydrogen

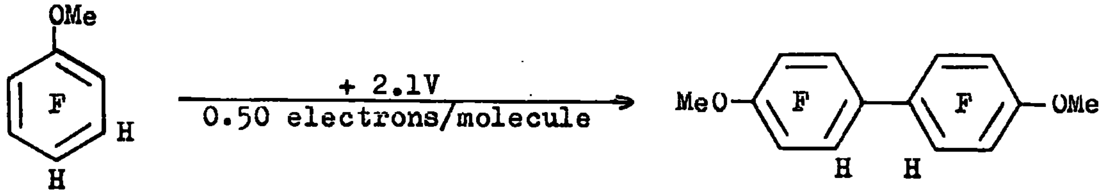
The compounds (110), (111) and (112) all contain ring hydrogen, making possible the kind of oxidative coupling reaction described on p. 65. Oxidation of 2,3,5,6-tetrafluoroanisole (110) and 2,3,6-trifluoroanisole (112) gave the corresponding dimers (113) and (114).



(110)

(113)

65% Current Efficiency



(112)

(114)

26% Current Efficiency

Dimerisation of (110) can only occur through the 4-position and the structure of the product (113) was easily confirmed by the presence of only two, equally-sized ^{19}F signals in its n.m.r. spectrum. Coupling of compound (112) might lead to several different dimers but the product was confirmed as exclusively (114) by comparison of its n.m.r. and i.r. spectra with those of an authentic sample.[115] This result, therefore, agrees with the coupling exclusively para to the methoxy-group, observed in hydrocarbon systems, (see p.66).

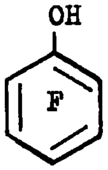
Oxidation of 2,4,5-trifluoroanisole (111), which has no para-hydrogen, gave no dimer, again in agreement with results from simple anisole derivatives.

A high yield of (113) was obtained using acetonitrile as the solvent, without the necessity of using a methylene chloride/trifluoroacetic acid mixture. It was thought that the ortho fluorines in (113) might prevent coplanarity of the two rings and raise the oxidation potential above that of the anisole derivative (110). It is known that if conjugation between the rings of biphenyl derivatives of this type is inhibited by bulky substituents, the oxidation potential is raised[116] and the angle between the rings of decafluorobiphenyl has been calculated as 50° from n.m.r. measurements.[117] The ultra-violet spectrum of (113) was compared with that of (110), which shows absorptions in cyclohexane solution at 264nm (ϵ 630) and 219 (ϵ 5,300). The dimer has an intense new absorption at 244nm (ϵ 18,300), clearly demonstrating that there is a large amount of conjugation between the rings, (see p.41). It seems, therefore, that (113) should itself be oxidisable at the potential used. The large yield of (113) obtained may mean that its radical cation is stable in acetonitrile and does not undergo any of the processes attributed to the radical cations of the dimers of simple anisole derivatives on p.65. Another possibility is that (113) is not adsorbed onto the anode as readily as (110), making its oxidation more difficult.

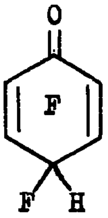
The yield of hexafluoro-2,2'-dihydro-4,4'-dimethoxybiphenyl (114) was much less and this is probably due to a decrease in stability of its radical cation. This is most likely attributable to the presence of two hydrogen atoms, allowing anodic substitution reactions such as hydroxylation and acetamidation to take place. It is unlikely that further coupling takes place, as the hydrogen atoms are not para to methoxy groups.

2. Pentafluoroanisole (109)

In pentafluoroanisole (109) the position para to the methoxy group is blocked by a fluorine atom. As might be expected, therefore, when it was oxidised at + 2.4V no coupled product was formed. The identity of the products, however, was undetermined. These consisted of a high-boiling red liquid, containing more than one component, which behaved rather strangely on g.l.c. at high temperature, with peaks appearing and disappearing as the conditions were changed. When the components were 'separated' by preparative g.l.c. a mixture was obtained. It seems likely, therefore, that unstable species were present, decomposing on the column. G.l.c. with mass spectroscopy gave evidence for the presence of two components with parent peaks at 184, which could be explained by species such as pentafluorophenol (115) and (116), but these may have resulted from decomposition in the mass spectrometer. There was no obvious explanation for a component with a parent peak at 217, which must either have resulted from decomposition or contain nitrogen but no simple acetamidation product has this mass.



(115)



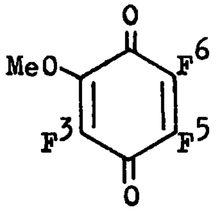
(116)

V.C ATTEMPTED ACETOXYLATIONS

As was explained on p.70, nuclear acetoxylation requires the presence of acetate ion and the derivatives investigated here had no alkyl side-chains. An acetic acid/sodium acetate solvent system could not be used, however, as the cell resistance became so high that the potentiostat could not reach the necessary oxidation potentials. When an acetonitrile/acetic acid mixture containing sodium acetate was used, it was found to be oxidised itself at the potentials necessary. For this reason, most of the reactions were performed in an acetonitrile/acetic acid mixture, containing tetraethylammonium fluoroborate as the electrolyte.

1. Pentafluoroanisole (109)

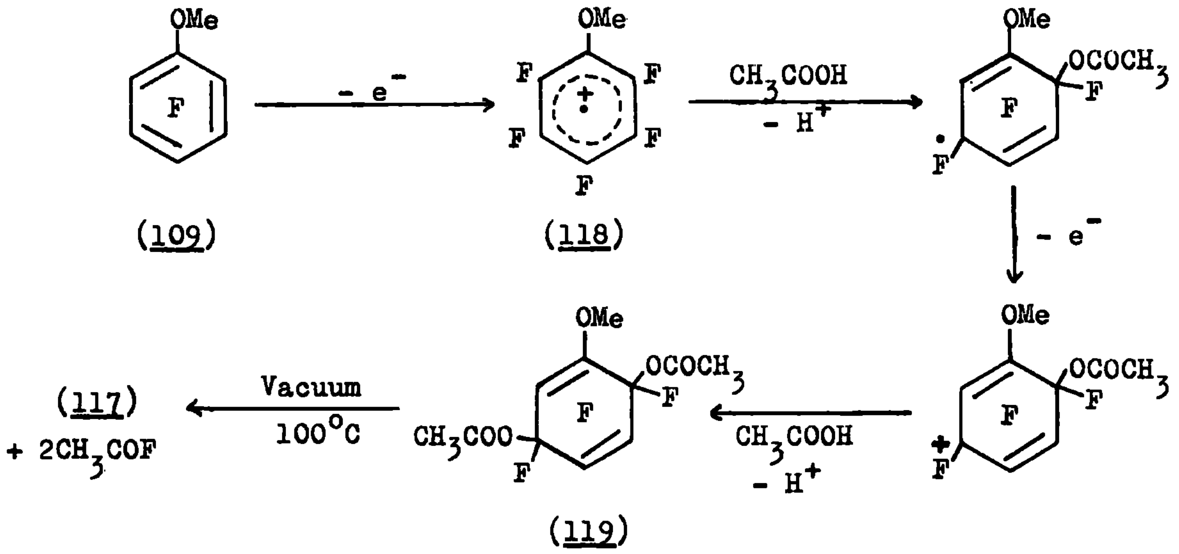
Pentafluoroanisole (109) was oxidised at + 2.4V in a solution of tetraethylammonium fluoroborate in a 3 : 1 mixture of acetonitrile and acetic acid. When 1.6 electrons/molecule were supplied the product was a viscous brown liquid, which decomposed during molecular distillation under reduced pressure, giving a volatile product, which was pumped off, and an orange sublimate. The sublimate gave a yellow solid on recrystallisation, which decomposed in the atmosphere and gave no satisfactory elemental analysis but had an n.m.r. spectrum consistent with methoxytrifluoro-p-benzoquinone (117).[118]



(117)

Assignment	Chemical Shift v. $CFCl_3$	Integration	Literature[118]
F^5 F^6	143.5ppm	2	144.9, 145.4ppm
F^3	152.7ppm	1	151.3ppm
	Chemical Shift v. T.M.S.		Literature[118]
CH_3	Doublet(J = 5Hz) 4.36ppm		Doublet(J = 3.6Hz) 4.16ppm

A possible route to (117) would be via formation of the diacetoxy-compound (119) and subsequent loss of acetyl fluoride:



Initial attack on the radical cation (118) probably occurs in the ortho position, as in the acetoxylation of anisole, but in this case there is no

H^+ to be displaced in a substitution reaction so further oxidation occurs. This is a two-electron process and the current efficiency for production of (117) was only 17%, calculated on this basis.

When (109) was oxidised under the same conditions and the reaction mixture treated with sodium carbonate to remove any trace of acetic acid, (117) was not obtained and the product was a yellow oil. G.l.c. showed this to contain a large number of components. It did not decompose on heating under vacuum but molecularly distilled. Its mass spectrum showed peaks at high masses, which could not be identified, and a large peak at 43, suggesting the presence of acetate groups. It appears that any (118) present must be attacked by the basic sodium carbonate solution but it is not known what the products are.

2. 2,3,5,6-Tetrafluoroanisole (110)

Compound (110) was also oxidised in the medium used above at + 2.4V and the reaction mixture neutralised. The product was a multi-component yellow oil similar to that above, except that it decomposed during molecular distillation under reduced pressure, leaving only a tar on the cold finger.

This compound was also oxidised in a solvent system similar to that above but, in addition, saturated with sodium acetate. This was itself discharged at + 2.4V, however, and there was no increase in current on adding (110). The product was an oil similar to that above, the only apparent difference being its orange colour.

EXPERIMENTAL

INSTRUMENTATION

Infra-red spectra were recorded on Perkin-Elmer Model 457 or 577 'Grating Infra-red Spectrophotometers'. Solid samples were pressed into homogeneous thin discs with potassium bromide. Liquids and low melting point solids were recorded as contact films between potassium bromide plates. Gaseous samples were recorded in gas cells with potassium bromide windows.

Ultra-violet spectra were recorded on a Unicam S.P.8000 or a Beckmann Model 25 spectrophotometer.

Mass spectra were recorded on A.E.I. M.S.9 spectrometer or a V.G. Micromass 12B linked with a Pye 104 gas chromatograph.

Hydrogen (^1H) nuclear magnetic resonance spectra were recorded on a Varian A56/60D spectrometer, operating at 60.0 MHz, with an ambient probe temperature of 40°C. Chemical shifts are quoted in ppm relative to T.M.S., downfield shifts being positive.

Fluorine (^{19}F) n.m.r. spectra were recorded on the Varian A56/60D, operating at 56.4 MHz, or a Brüker HX90E operating at 84.67 MHz, with an ambient probe temperature of 22°C. Chemical shifts are quoted relative to $CFCl_3$, upfield shifts being positive. A variable temperature facility was available on the Varian instrument.

Carbon (^{13}C) n.m.r. spectra were recorded on the Brüker HX90E with a Fourier Transform facility. Shifts are quoted relative to natural abundance T.M.S., downfield shifts being positive.

Quantitative gas liquid chromatographic analysis (g.l.c.) was carried out on a Griffin and George D6 Gas Density Balance (G.D.B.) or a Varian Aerograph 920 G.D.B. For these instruments, when correctly standardised, the number of moles of any compound in a mixture is proportional to its peak area. Columns used were packed with 30% silicone gum rubber SE-30 (column O); 20% di-isodecylphthalate (column A); 17% 2-cyanoethylmethylsilicone (column Z); or 30% trixylenylphosphate (column T); all on a support of Chromosorb P. Preparative scale g.l.c. was performed on Varian Aerograph 920 or 'Autoprep' instruments, or a Perkin-Elmer F21, using the above columns.

Carbon, nitrogen and hydrogen analyses were obtained using a Perkin-Elmer 240 Elemental Analyser. Analysis for halogens was carried out as described in the literature.[119]

Melting points and boiling points were determined at atmospheric pressure and are uncorrected. Boiling points were recorded by the Siwoloboff method or during fractional distillation.

CHAPTER VI

EXPERIMENTAL FOR CHAPTER III

VI.A REAGENTS

Pentachloropyridine was obtained from I.C.I. and pentafluoropyridine was prepared from it by technical staff, by published routes.[120] Other pyridine derivatives were prepared by published routes, or donated by other members of this laboratory.

Dimethylformamide (D.M.F.) was purified by fractional vacuum distillation (66mm, ca. 79°C) from firstly anhydrous sodium carbonate and secondly dry molecular sieve (type 4A). Sulpholane was fractionally distilled twice under vacuum. Acetonitrile was repeatedly distilled from phosphorus pentoxide. All three were stored over dry molecular sieve (type 4A) at room temperature, under an atmosphere of dry nitrogen.

Tetraethylammonium fluoroborate was prepared simply by mixing hot, saturated, aqueous solutions of tetraethylammonium bromide and sodium fluoroborate and allowing to cool. The solid was filtered off and recrystallised from aqueous methanol, until no residual bromide could be detected using silver nitrate solution. It was dried by alternately heating to 150°C under vacuum and crushing to a fine powder, and stored under nitrogen.

Mercury was doubly distilled.

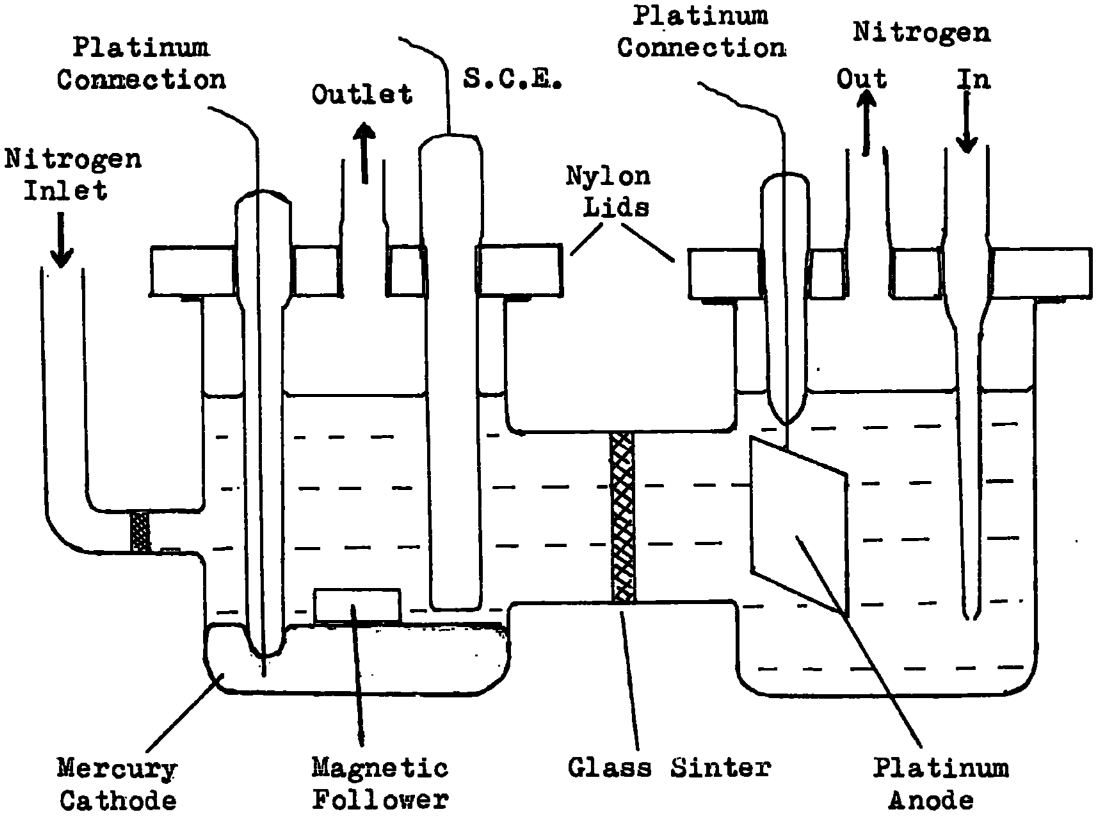
VI.B PREPARATIVE REDUCTIONS

1. General

(a) Electrochemical Cells

Unless otherwise stated, preparative scale reductions were performed in an 'H-cell' of the design shown in Figure VI.1. This had a mercury pool cathode of approximately 3.5cm diameter, and a flat platinum sheet anode

Figure VI.1 The H-Cell.



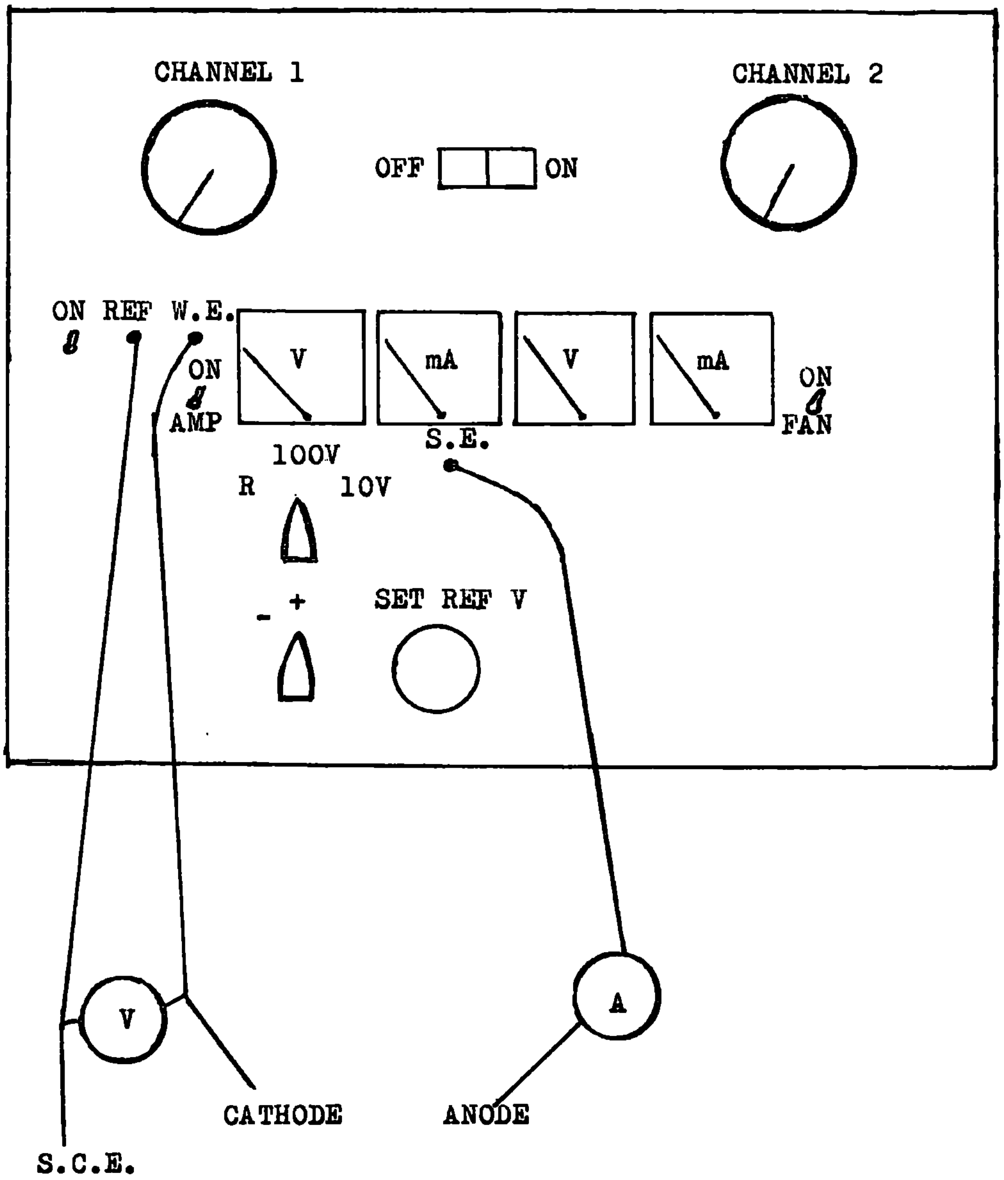
approximately 3cm square. The reference electrode was a Pye-Unicam 303NS saturated calomel electrode, protected from the solution by a built-in sinter, which was immersed directly in the cell with the tip close to the cathode. When filled to the level normally used, the cell held 170 mls of solution, with approximately 80 mls in the cathode compartment.

A larger two-compartment cell was also available, with the anode compartment above the cathode compartment, so that the 11cm diameter mercury cathode and 7cm square platinum anode were parallel. This held approximately 400 mls of solution, most being in the cathode compartment.

(b) Potentiostat

The potentiostat used was a custom built model loaned by the Electricity Council, incorporating a D.C.300 watt amplifier. This had two channels, which could be used independently. Figure VI.2 shows a diagramatic representation of the controls and wiring involved in using channel 1.

Figure VI.2 Wiring for reductions using Channel 1.



An identical set of controls is present for channel 2.

To operate the potentiostat it is first switched on at the main on/off switch at the top of the instrument and the switch marked 'ON AMP'. The fan is switched on and the dials marked 'CHANNEL 1' and 'CHANNEL 2' turned fully clockwise. The potentiostat is then allowed to warm up for

15 minutes.

The working electrode (in this case the cathode) is connected to the terminal marked 'W.E.' and the reference to 'REF'. A voltmeter is connected between the two for measuring the potential between them. A Fluke 8000A digital multimeter was used for this purpose. The auxiliary electrode is connected, via an ammeter, to 'S.E.'. The ammeter measures the current through the cell. To perform reductions the switch marked with '+' and '-' must be set to the '+' position.

With a solution in the cell, the final 'ON' switch to the left of the 'REF' and 'W.E.' terminals can be turned on. This must never be on with the circuit broken or the potentiostat may be damaged. The potential of the working electrode relative to the reference can now be set using the dial marked 'SET. REF. V.'

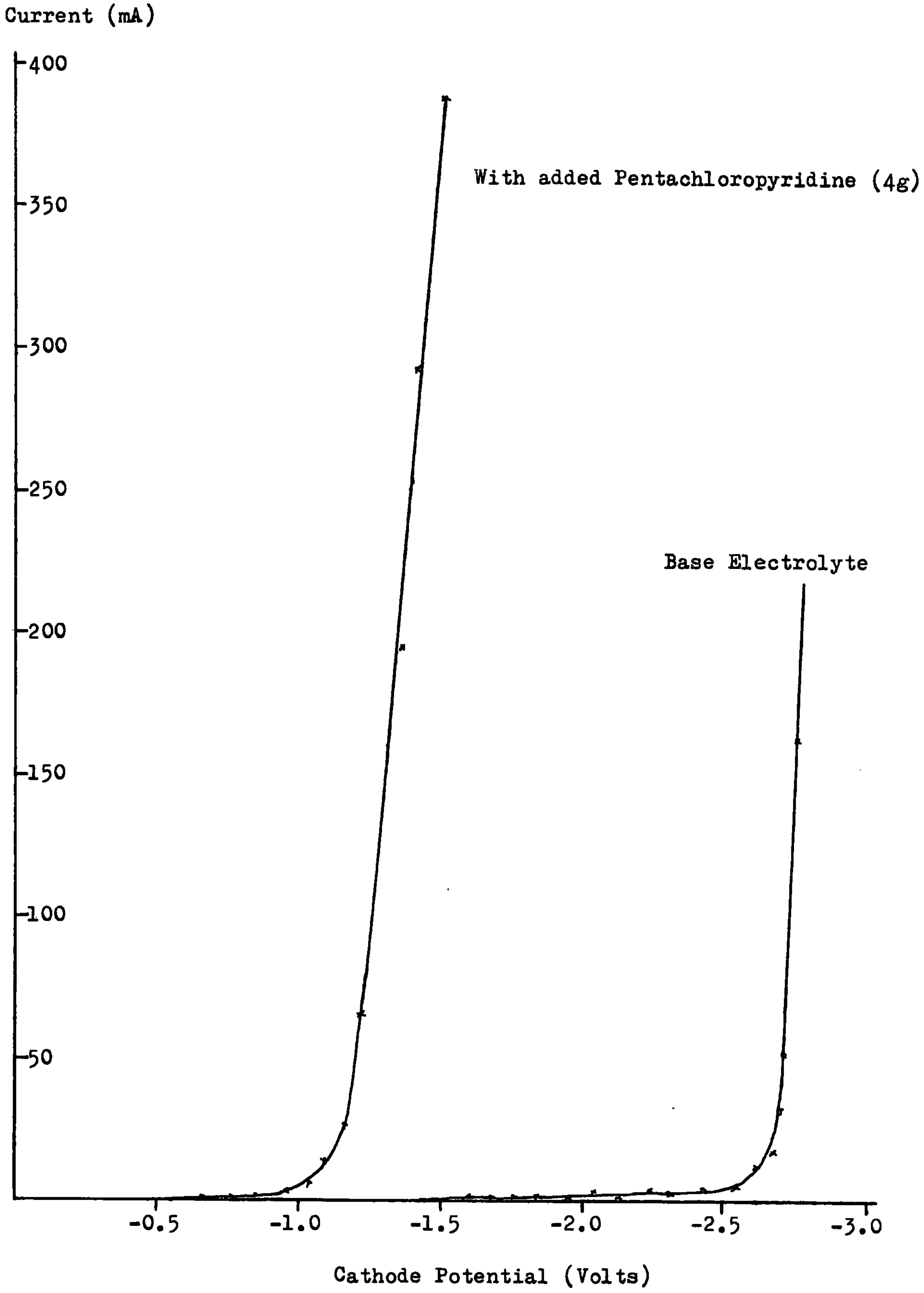
The voltmeter on the front of the instrument measures the total voltage across the cell, and its full scale deflection is either 10 or 100V, depending on the position of the switch below it. At a voltage of about 50V the potentiostat starts to lose control of the working electrode potential. The ammeter on the potentiostat measures some internal current reading and is unimportant.

(c) Experimental Procedure

The H-cell was filled with 170ml of solvent containing tetraethylammonium fluoroborate (T.E.A.F.) electrolyte. Various weights of electrolyte were used between 6g (0.16M) and 12g (0.32M). The amount did not appear to affect the reactions, so generally 6g was used. The solution was deoxygenated by bubbling dry nitrogen through the cell. A potential sweep was then performed by noting the current at 0.1V intervals down to the limiting cathode potential.

The substrate (2-6g) was then added to the cathode compartment

Figure VI.3 Current/potential Curves.



and the sweep repeated. Representative current/potential curves obtained with and without added substrate are shown in Figure VI.3 for pentachloropyridine. From these a potential was chosen with negligable background current and a current due to the substrate of 100 to 400mA. The electrolysis was performed with the cathode potential controlled at this value. When necessary the cell was cooled in a water bath at room temperature. The amount of charge passed was followed graphically and the reaction stopped after a suitable amount had passed.

2. Reduction of Pentafluoropyridine and Related Compounds

(a) Pentafluoropyridine (53)

(i) In D.M.F.

The details of a number of reductions, performed at -1.80V (v. S.C.E.) on a mercury cathode, are summarised in Table VI.1, overleaf. The experimental method was as described above. Three different work-up methods were employed:

Method 1 All volatiles, including D.M.F., were removed by transference under vacuum into a cold trap. A white sublimate A collected in the transfer arm. The involatile residue was extracted with methylene chloride, washed well, dried ($MgSO_4$), and the solvent distilled off. Sublimation of the residue under reduced pressure (0.05mm, 50°C) gave more A and left a tarry residue, which gave no further sublimate at up to 160°C. The residue was shown by thin layer chromatography, using toluene as eluent, to be a multicomponent mixture.

The original volatiles were investigated by g.l.c. (col. O, 150°C) to determine the amount of unreduced pentafluoropyridine (53).

The sublimate A was identified as octafluoro-4,4'-bipyridyl (56), by comparison of its ^{19}F n.m.r. and infra-red spectra with those of an authentic sample.[75] λ_{max}(cyclohexane) 222nm (ε 8,500), 281nm (ε 8,200); n.m.r. spectrum No.1; i.r. spectrum No.1.

Table VI.1 Results of reductions of pentafluoropyridine (53) in D.M.F.

Initial Weight (53)	Charge Passed		Work-up Method	Material Recovered			Current Efficiency for (56)
	Faradays	e/molecule		(53)	Tar	Bipyridyl (56)	
2.52g	0.0131	0.88	1	0.75g	0.98g	0.24g	12%
6.19g	0.0066	0.18	1	4.69g	0.41g	0.52g	52%
2.50g	0.0070	0.47	2	0.31g	0.17g	0.29g	28%
11.08g	0.0093	0.14	2	9.57g	0.55g	0.50g	36%
2.65g	0.0135	0.86	3	0.41g	0.85g	0.80g	49%

N.B. The current efficiency for the production of (56) was calculated on the basis of two electrons being required for the production of one molecule of (56), (see Chapter 1, p.8).

Using this method, some of the bipyridyl (56) transferred with the volatiles and was not recovered.

Method 2 The amount of (53) remaining was determined by g.l.c. and the reaction mixture then added to a large excess of water. This was then extracted thoroughly with methylene chloride and the organic phase washed well, dried and the solvent distilled off. Finally sublimation under reduced pressure yielded the bipyridyl (56).

This method was plagued by the tendancy of the reaction mixture to form emulsions on dilution with water, and also the large volumes of water necessary to achieve separation.

Method 3 The reaction mixture was distilled under reduced pressure (42mm, 68°C) and the distillate investigated by g.l.c. to determine the amount of unreduced (53). The residue was added to methylene chloride, washed well, dried and the solvent distilled off. Sublimation of the residue yielded the bipyridyl (56).

This method was only used on one occasion but the yield obtained after passage of a lot of charge suggests it might be the most efficient.

(ii) In Sulpholane

Pentafluoropyridine (53) (2.56g, 15.1 m.moles) was reduced at -1.80V on a mercury cathode, in a solution of T.E.A.F. (6g) in sulpholane (170ml). 0.0108 Faradays of charge were passed (0.71 electrons/molecule). The reaction mixture was flash distilled twice at 90°C under vacuum, to remove volatile components from the sulpholane. These were then pumped gently to remove unreacted (53) and sublimation of the residue (0.05mm, 50°C) yielded the bipyridyl (56) (0.78g, 48% C.E.).

(iii) In Acetonitrile

Pentafluoropyridine (53) (2.27g, 13.4 m.moles) was reduced at -1.80V in a solution of T.E.A.F. (6g) in acetonitrile (170ml). The current was very erratic, and at times the potentiostat lost control of the cathode potential. After passage of an unknown quantity of electricity, the acetonitrile was distilled off and the residue washed well with water and filtered, giving a black solid (1.70g). On sublimation under reduced pressure (0.05mm) at up to 200°C, this yielded no material. T.l.c. in toluene showed it to be a multicomponent mixture.

(iv) In D.M.F. Containing Hydroquinone

Pentafluoropyridine (53) (7.52g, 44.5 m.moles) was reduced at -2.40V in a solution of T.E.A.F. (6g) in D.M.F. (170ml), with hydroquinone (2.66g, 24.2 m.moles) dissolved in the cathode compartment. 0.0180 Faradays of electricity were passed (0.40 electrons/molecule of (53)). The reaction mixture was fractionated under reduced pressure and the first fraction shown by g.l.c./mass spectroscopy (col. O, 90°C) to contain a compound later identified as 4-H-tetrafluoropyridine (61) (0.63g, 46% C.E., assuming 2 electrons required/molecule of (61)). This was separated by preparative g.l.c. and identified by comparison of its ^{19}F n.m.r. and infra-red spectra those of an authentic sample,[77] (n.m.r. spectrum No.2; i.r. spectrum No.2).

The residue from the fractionation was added to methylene chloride, washed, dried and the solvent distilled off. Sublimation of the residue under reduced pressure (0.05mm, 50°C) yielded no bipyridyl (56).

(v) In D.M.F. Saturated with Carbon Dioxide

The cell was filled with a solution of T.E.A.F. (12g) in D.M.F. (170ml), which was then deoxygenated by bubbling dry nitrogen. This was then replaced with a stream of dry carbon dioxide for half an hour before commencing the reduction. Pentafluoropyridine (53) (3.54g, 20.9 m.moles) was added and reduced at -1.80V, maintaining the flow of carbon dioxide at all times. 0.0160 Faradays of charge were passed (0.77 electrons/molecule). The volatiles were removed by transference under vacuum into a cold trap, and the residue washed with water, filtered and dried in a dessicator to give a brown solid **A** (1.25g) and an aqueous solution **B**.

The solid **A** was sublimed under reduced pressure (0.05mm, 80°C) to give the bipyridyl (56) (0.09g). Sublimation at 160°C yielded no more material.

The aqueous solution **B** was acidified with nitric acid and solvent extraction with ether yielded only a small amount of a high boilng liquid, identified as D.M.F. from its i.r.spectrum.

The original volatiles from the catholyte were fractionated under reduced pressure (24mm, 57°C) and the early fractions were shown by g.l.c to contain (53) (ca. 1.5g). The residue was added to methylene chloride, washed, dried ($MgSO_4$) and the solvent distilled off. Sublimation under reduced pressure yielded more of the bipyridyl (56) (0.08g; Total 0.17g, 7% C.E.).

(b) 4-Bromotetrafluoropyridine (59) in D.M.F.

4-Bromotetrafluoropyridine (59) (2.53g, 11.0 m.moles) was reduced at -1.80V in a solution of T.E.A.F. (6g) in D.M.F. (170ml). 0.0118 Faradays were passed (1.07 electrons/molecule). The volatiles were removed by distillation under reduced pressure (42mm, 69°C). The early fractions were shown by g.l.c. with mass spectroscopy (col. Z, 140°C) to contain tetrafluoropyridine (61) (ca. 0.16g, 18% C.E.). The residue was added to methylene chloride, washed, dried and the solvent distilled off. Sublimation under reduced pressure yielded a moist solid sublimate, shown by n.m.r. to be mainly the bipyridyl (56) (0.10g, 6% C.E.), but contaminated with the starting material (59).

(c) Octafluoro-4,4'-bipyridyl (56) in D.M.F. Saturated with Carbon Dioxide

Octafluoro-4,4'-bipyridyl (56) (2.81g, 9.36 m.moles) was reduced at -1.20V in a solution of T.E.A.F.(6g) in D.M.F. (170ml) saturated with carbon dioxide, with carbon dioxide being continuously bubbled through the solution. 0.00732 Faradays of charge were passed (0.78 electrons/molecule). The deep turquoise-blue catholyte turned brown on exposure to the air. The volatiles were removed by transference under vacuum into a cold trap, added to ether, washed thoroughly with water, dried and the ether removed by distillation. Sublimation under reduced pressure yielded (56) (0.27g).

The original involatile residue from the catholyte was added to water and extracted with methylene chloride. Treatment of the organic phase as above yielded a further 0.49g of (56), showing impurities in its i.r. spectrum which were not further investigated; and a tarry brown residue (0.52g). The aqueous phase was acidified and solvent extraction yielded no acidic products.

3. Reduction of Pentachloropyridine and Related Compounds

(a) Pentachloropyridine (54) in D.M.F.

(i) On a Mercury Cathode

Pentachloropyridine (54) (5.49g, 21.8 m.moles) was reduced at -1.40V in a solution of T.E.A.F. (6g) in D.M.F. (170ml). A purple colour was formed during the electrolysis. 0.0107 Faradays of charge passed (0.49 electrons/molecule). The solvent was removed from the catholye by transference under vacuum into a cold trap. The residue was washed with water, and the insoluble solid washed with methylene chloride to leave an insoluble white solid (0.59g), identified after recrystallisation from D.M.F. as bis-tetrachloropyridyl mercury (64) (17% C.E. assuming requirement of 2 electrons/molecule of (64)),m.p. ca.250°C with decomposition. (Found: C, 18.7; N, 4.3; Cl, 45.2%; M^+ (^{202}Hg, ^{35}Cl), 630; $C_{10}Cl_8HgN_2$ requires C, 19.0; N, 4.4; Cl, 44.9%; M, 630), i.r.spectrum No.3.

The aqueous phase was extracted well with methylene chloride and all of the methylene chloride extracts combined, washed, dried,and the solvent removed by distillation. Sublimation under reduced pressure (0.05mm) at up to 140°C yielded several fractions of white solid (total: 3.50g), shown by g.l.c./mass spectroscopy (col O, 220°C), n.m.r. and i.r. spectroscopy to be mixtures of 4-H-tetrachloropyridine (63) (total wt.: 0.66g, 57% C.E. assuming 2 electrons/molecule) and unreduced (54) (total wt.: 2.84g). A sample of (63) from a different experiment was characterised as described later. Sublimation of the remaining residue at 200°C yielded a sticky orange solid (0.22g), which could not be recrystallised. Its mass spectrum showed clusters at $^m/e$ 630, ((64)); 428, ($C_{10}N_2Cl_8$); 394, ($C_{10}N_2Cl_7H$); and higher unidentified masses.

(ii) On a Lead Cathode

A piece of lead plate, to be used as the cathode, was preconditioned by making it alternately the cathode and the anode in a solution of sulphuric acid. This was then washed and dried, and used to reduce a solution of pentachloropyridine (54) (4g, 15.9 m.moles) in T.E.A.F./D.M.F. at -1.50V. There was some difficulty in maintaining the current, due to the formation of an insoluble film on the lead. This was periodically removed by briefly reversing the polarity. The purple colour observed previously again formed. 0.0138 Faradays of charge were passed (0.87 electrons/molecule). The lead was covered in a black film and, after cleaning, was found to have decreased in weight by 0.15g (0.7 m.moles).

The solvent was removed from the catholyte by transference under vacuum into a cold trap and the residue washed well with water and dried in a dessicator (P_2O_5) to give a brown solid (3.11g), almost entirely soluble in methylene chloride. Sublimation under reduced pressure (0.05mm, 80°C) gave a white solid (2.29g), shown by g.l.c. (col. O, 220°C) to be a mixture of unchanged (54) and tetrachloropyridine (63) (ca. 0.23g, 15% C.E.). Sublimation at 175°C over several days yielded a yellow solid, identified as octachloro-4,4'-bipyridyl (65) (0.26g, 9% C.E.), m.p. (from CCl_4) 218-220°C (lit.[121] 221-222°C). (Found: C, 27.6; N, 6.1; Cl, 65.2%; M^+ (^{35}Cl), 428; $C_{10}Cl_8N_2$ requires C, 27.8; N, 6.5; Cl, 65.7%; M, 428). λ_{max} (cyclohexane) 236nm (ε 23,400), 300nm (ε 11,800); i.r.spectrum No.4; ^{13}C n.m.r. spectrum No.3.

An intractible brown tar (1.30g) remained as the sublimation residue.

N.B. Preparation of Octachloro-4,4'-bipyridyl (65)

An uncharacterised mixture of polychlorinated 4,4'-bipyridyls supplied by I.C.I. Mond Division (6.79g) was mixed with phosphorus pentachloride (80g) and sealed in a nickel-lined autoclave (500ml). Silver washers were used in an attempt to avoid leakages previously experienced using copper. This was heated to 300°C and kept at that temperature for 7 hours. It was then allowed to cool and vented in a fume cupboard, when it became evident that the autoclave had leaked. Nevertheless, extraction with methylene chloride and iced water, followed by separation of the organic phase, drying, and distillation of the solvent, yielded a pale brown solid with identical i.r. and mass spectra to the octachloro-4,4'-bipyridyl (65) obtained previously (1.57g).

(iii) On a Platinum Cathode

A piece of thin platinum sheet identical with the anode was used as the cathode. Pentachloropyridine (54) (4.06g, 16.2m.moles) was reduced at -2.0V in a solution of T.E.A.F. (12g) in D.M.F. (170ml). The potential used was more negative than previously due to an inability to obtain a reasonable current at lower potentials. It was probably in error due to the large gap between the S.C.E. and the cathode surface. The normal purple colour formed during the electrolysis. 0.0160 Faradays of charge was passed (0.99 electrons/molecule). The catholyte was added to a large excess of water and extracted with methylene chloride. The extracts were washed, dried, and the solvent distilled off. Sublimation of the residue under reduced pressure (0.05mm, 80°C) yielded a white sublimate (1.72g), shown by g.l.c./mass spectroscopy to contain mainly unreacted (54) and the tetrachloropyridine (63) (ca. 0.64g, 37% C.E.) with a trace of a trichloropyridine (M^+, 181) at lower retention time. A tarry residue remained (0.46g).

(b) Reductions in the Presence of Carbon Dioxide

(i) Pentachloropyridine (54)

This reaction was performed on several occasions, and some results are summarised in Table VI.2. The experimental procedure was the same in

Table VI.2

Weight (54)		Charge Passed	Products			Decarboxylation Products[a]			
			C_5NCl_4H		Acid Mixture	C_5NCl_4H		C_5NCl_4—C_5NCl_3H	
Initial	Final	e/mol.	Wt.	C.E.	Wt.	Wt.	C.E.	Wt.	C.E.
2.11g	0.79g	1.12	0.02g	2%	0.95g	0.06g	6%	0.40g	43%
10.0g	5.01g	1.00	0.51g	12%	3.90g	0.50g	11%	1.97g	50%
10.0g	0.98g	1.90	1.02g	12%	6.52g	1.49g	18%	2.61g	35%

a : The weights of the decarboxylation products are extrapolated from those obtained from a small sample of the acid mixture. The current efficiencies assume 2 electrons/molecule of C_5NCl_4H and 4 electrons/molecule of C_5NCl_4—C_5NCl_3H.

every case, so only one run is described in detail. Reductions on 10g of (54) were performed in the large 400ml cell,and on 2.11g in the normal H-cell.

Pentachloropyridine (10.0g, 39.8 m.moles) was reduced at -1.30V in a solution of T.E.A.F. (20g) in D.M.F. (400ml) saturated with carbon dioxide. Carbon dioxide was bubbled continuously through the cell during the electrolysis. No colour formed during the reaction. 0.0398 Faradays of electricity was passed (1.0 electrons/molecule). The volatiles were removed from the catholyte by transference under vacuum into a cold trap, leaving an involatile solid A. The volatiles were then fractionally distilled under reduced pressure and the residue from this distillation was added to water and extracted with methylene chloride. After washing, drying, and distilling off the solvent, the residual solid was sublimed under reduced pressure (0.05mm, 80°C) to give a white sublimate (0.27g), shown by g.l.c. to contain (54) and 4-H-tetrachloropyridine (63).

The involatile solid A was added to water and filtered to give a white solid (5.76g) which gave another mixture of (54) and (63) on sublimation under reduced pressure. Sublimation at up to 180°C yielded no further material. The combined sublimate was shown by g.l.c. to contain approximately 5.01g of (54) and 0.52g of (63) (12% C.E.).

The aqueous phase from A was acidified with hydrochloric acid and a white solid B (3.57g) filtered off. Concentration of the aqueous phase yielded more B (0.33g). B showed a strong i.r. absorption at 1690 cm^{-1} (C=O), but no large O-H absorption. Its mass spectrum showed large peaks at $^{m}/e$ 394 ($C_{10}N_2Cl_7H$), and 215 (C_5NCl_4H) due to decarboxylation of the corresponding acids in the mass spectrometer, with a very large peak at 44 (CO_2). B was only slightly soluble in water, giving an acidic solution. Recrystallisation from water gave various fractions, all with slightly differing i.r.spectra. It dissolved readily in sodium hydroxide solution and was precipitated on reacidification, with a slightly changed i.r. spectrum. A sample of B (1.03g) was heated to 150°C under reduced pressure and a large amount of gas was evolved (presumably CO_2). The remaining solid was then fractionally sublimed under reduced pressure (0.05mm) to give:

(i) At 80°C ; a white sublimate, identified as 4-H-tetrachloropyridine (63) (0.13g), m.p. 90-91°C (from pet. ether, 60-80°fraction), (lit.[83] 90.5-91.5°C; 3-H-tetrachloropyridine, 37.5-38°C; 2-H-tetrachloropyridine, 21-22°C). (Found: C, 28.0; H, 0.2; N, 6.5; Cl, 65.1%; M^+ (^{35}Cl), 215; C_5HCl_4N requires C, 26.7; H, 0.5; N, 6.5; Cl, 65.4%; M, 215). λ_{max} (cyclohexane) 233nm (ϵ 12,600), 292nm (ϵ 6,700); i.r.spectrum No.5; n.m.r. spectrum No.4.

(ii) At 140°C ; a white sublimate, identified as a heptachlorobipyridyl (66) (0.52g), m.p. 171.5-173°C (from CCl_4), (lit.[84] 3-H-heptachloro-4,4'-bipyridyl, 171-172°C). (Found: C, 30.5; H, 0.2; N, 7.4; Cl, 62.8%; M^+ (^{35}Cl), 394; $C_{10}HCl_7N_2$ requires C, 30.2; H, 0.3; N, 7.1; Cl, 62.5%; M, 394). λ_{max} (cyclohexane) 232nm (ϵ 22,600), 294nm (ϵ 10,200); i.r.

spectrum No.6; n.m.r. spectrum No.5.

(iii) A brown solid residue (0.27g), with an i.r. spectrum very similar to tetraethylammonium chloride. On washing well with water, only 0.04g of insoluble residue remained.

The current efficiencies for the production of (63) and (66) via the corresponding acids, were calculated assuming the consumption of 2 and 4 electrons/molecule respectively to be 11% and 50%.

(ii) Octachloro-4,4'-bipyridyl (65)

Octachloro-4,4'-bipyridyl (65) (1.98g, 4.59 m.moles) was reduced at -1.3V in a solution of T.E.A.F. (6g) in D.M.F. (170ml) saturated with carbon dioxide. The bipyridyl (65) was not all in solution initially. The catholyte turned yellow/brown during the reaction and most of the bipyridyl dissolved. 0.00694 Faradays of charge were passed (1.51 electrons/molecule). The solvent was removed by transference under vacuum into a cold trap, and the residue shaken with water, filtered, and dried in a dessicator (P_2O_5), to give an off-white solid (1.27g). Sublimation under reduced pressure (0.02mm) at up to 185°C gave various yellow solids (0.84g), shown by their i.r. spectra to be (65) containing impurities, which were not further investigated.

The aqueous phase was extracted with ether to remove residual D.M.F., acidified with dil. HNO_3, and re-extracted. These extracts were dried ($MgSO_4$) and the ether removed under vacuum to give an oily yellow solid (0.43g). This was heated to 160°C under reduced pressure and no decarboxylation was observed. On sublimation under reduced pressure (0.05mm, 160°C) a colourless liquid was observed on the cold finger. The solid residue was washed with a small amount of water and dried (P_2O_5 dessicator) to give a brown residue (0.31g). This was then reheated to 160°C and finally sublimed at this temperature under reduced pressure to give a sticky colourless solid (0.10g). This had an i.r. spectrum similar to the acid mixture obtained from (<u>54</u>). Its mass spectrum showed peaks at $^{m}/e$ 394 ($C_{10}N_2Cl_7H$, small) and 360 ($C_{10}N_2Cl_6H_2$, large), resulting from decarboxylation in the mass spectrometer; and very small peaks at higher masses, probably due to the acids. No decarboxylation was observed on boiling a solution of the mixture in dilute sodium hydroxide solution, and the solid was reprecipitated on acidification.

(iii) <u>Hexachlorobenzene (71)</u>

Hexachlorobenzene (<u>71</u>) (2.60g, 9.13 m.moles) was reduced at -1.60V in a solution of T.E.A.F. (6g) in D.M.F. (170ml) saturated with carbon dioxide. The substrate was only partially dissolved initially and did not dissolve completely during the reaction. 0.0147 Faradays were passed (1.61 electrons/molecule), with very little colour formation. The D.M.F. was removed from the catholyte by transference under vacuum into a cold trap. The residue was shaken with water to give a white solid (0.63g), identified as unchanged (<u>71</u>) by its i.r.spectrum. Acidification of the aqueous phase with HNO_3 gave a white solid, which was dried in a vacuum dessicator (P_2O_5) (0.77g). This had a strong i.r. absorption at 1732 cm^{-1} (C=O) and a broad O-H absorption, characteristic of a carboxylic acid. Its mass spectrum showed large peaks at $^{m}/e$ 248 (C_6HCl_5) and 214 ($C_6H_2Cl_4$), due to decarboxylation in the mass spectrometer, with small peaks visible due to the corresponding acids at 292 (C_6Cl_5COOH) and 258 (C_6Cl_4HCOOH). A sample (0.44g) was decarboxylated by heating to 190°C under reduced pressure and sublimation of the product at this temperature and 0.05mm pressure gave a white sublimate (0.32g) and a brown residue (0.06g). The sublimate was resublimed at 55°C and gave 0.31g of material.

The sublimate above was investigated by g.l.c. (cols. O and Z, 250°C), which showed two components, identified by g.l.c./mass spectroscopy as pentachlorobenzene (72) (M^+, 248) (69%; 20% C.E.) and tetrachlorobenzene (M^+, 214) (31%; 21% C.E.). ^1H n.m.r. in CCl_4 showed three signals at 7.46, 7.47 and 7.32 ppm relative to internal T.M.S. These were assigned to pentachlorobenzene (72), 1,2,4,5-tetrachlorobenzene (74) and 1,2,3,5-tetrachlorobenzene (73) respectively, by comparison with literature values.[86] Accurate integration was impossible due to the closeness of the first two peaks, but the ratio of the latter two smaller peaks was approximately 1 : 1 from their peak heights.

(c) Reduction of Pentachloropyridine (54) in the Presence of Alkyl Halides

(i) With Iodomethane

Pentachloropyridine (54) (4.0g, 15.9 m.moles) was reduced at -1.20V on a mercury cathode, in a solution of T.E.A.F. (6g) in D.M.F. (170ml), with iodomethane (4.0g, 28.2 m.moles) dissolved in the cathode compartment. An orange colour was produced in the catholyte during the reduction, and a white precipitate. 0.0303 Faradays of charge were passed (1.90 electrons/molecule). The white solid (2.10g) was filtered from the catholyte and identified as tetraethylammonium iodide, by comparison of its i.r. spectrum with an authentic sample. The catholyte was concentrated by transference of the solvent into a cold trap under vacuum, and a further 1.18g of the iodide filtered off. The remainder of the solvent was removed as above and the residue extracted with water and methylene chloride, leaving an insoluble yellow solid (0.42g), identified from its mass spectrum as mercuric iodide (M^+ (^{202}Hg), 456). The organic phase was washed well, dried and the solvent distilled off, to leave a moist solid (1.82g). This was transferred under vacuum at 60°C, to give:

(i) A transferred liquid (0.54g), shown by g.l.c./mass spectroscopy (col. O, 200°C) to contain mainly chloroform and 4-H-tetrachloropyridine

(<u>63</u>), with a small amount of a trichloropyridine.

(ii) A solid condensed in the transfer arm (0.47g), showing two components on g.l.c. (col. O, 200°C), in the ratio 55 : 45. G.l.c./mass spectroscopy showed the first to be (<u>63</u>) and the second to be a mixture, with parent peaks at 249 ((<u>54</u>)) and 229 ($C_5NCl_4CH_3$) of roughly equal size.

(iii) An involatile brown residue (0·81g). Sublimation under reduced pressure (0.05mm) at up to 160°C yielded only a trace of viscous liquid.

(ii) <u>With Benzyl Chloride</u>

Pentachloropyridine (4.12g, 16.4 m.moles) was reduced at -1.20V on a mercury cathode, in a solution of T.E.A.F. (6g) in D.M.F. (170ml), with benzyl chloride (6.10g, 48.2 m.moles) dissolved in the catholyte. 0.0173 Faradays of charge were passed (1.06 electrons/molecule), and a purple colour formed in the catholyte. The D.M.F. was removed by transference under vacuum into a cold trap, and the residue extracted with methylene chloride, washed, dried,and the solvent distilled off, to give a brown liquid (3.80g). This was shown by g.l.c. (col. O, 250°C) to contain methylene chloride, benzyl chloride, 4-H-tetrachloropyridine (<u>63</u>) and pentachloropyridine (<u>54</u>). This was transfered into a cold trap under vacuum at 60°C past a cold finger, to give:

(i) A transfered liquid (2.0g), shown by g.l.c. to be mainly benzyl chloride.

(ii) A white sublimate on the cold finger, shown by g.l.c. to be mainly (<u>63</u>) and (<u>54</u>) in an approximate ratio of 56 : 44 (1.12g; C.E. for production of (<u>63</u>): 34%).

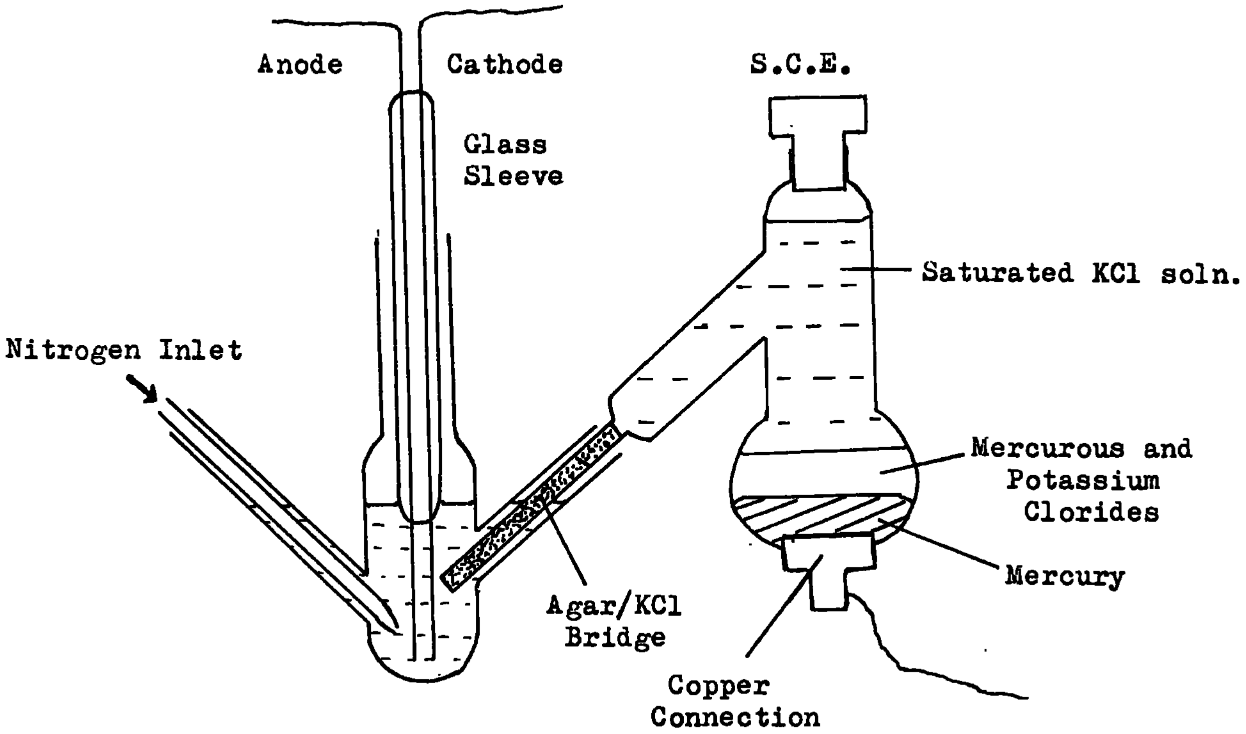
(iii) A brown residue (0.68g), showing a large number of i.r. stretching frequencies, including aromatic C-H stretch between 3004 and 3010 cm^{-1}. Sublimation at up to 160°C under reduced pressure (0.05mm) yielded no material.

VI.C VOLTAMMETRY

1. Single-Sweep Voltammetry

The single-sweep voltammetry and cyclic voltammetry at sweep rates up to 100 mV/sec was performed on a Beckmann Electroscan 30 electroanalytical instrument. The cell used was a microcell of approximately 2.5ml capacity (Figure VI.4). The cathode and anode were parallel cylindrical platinum wires of 0.5mm diameter, sealed in glass to maintain a constant cell geometry, with a separation of 2.5mm and exposed length of 20mm. The reference electrode was an S.C.E. with a side arm containing an agar/KCl salt bridge, which was immersed in the cell with the tip close to the cathode. The cathode potentials relative to this were checked using a Fluke 8000A Digital Multimeter.

Figure VI.4 Micro-cell for Single-Sweep Voltammetry.



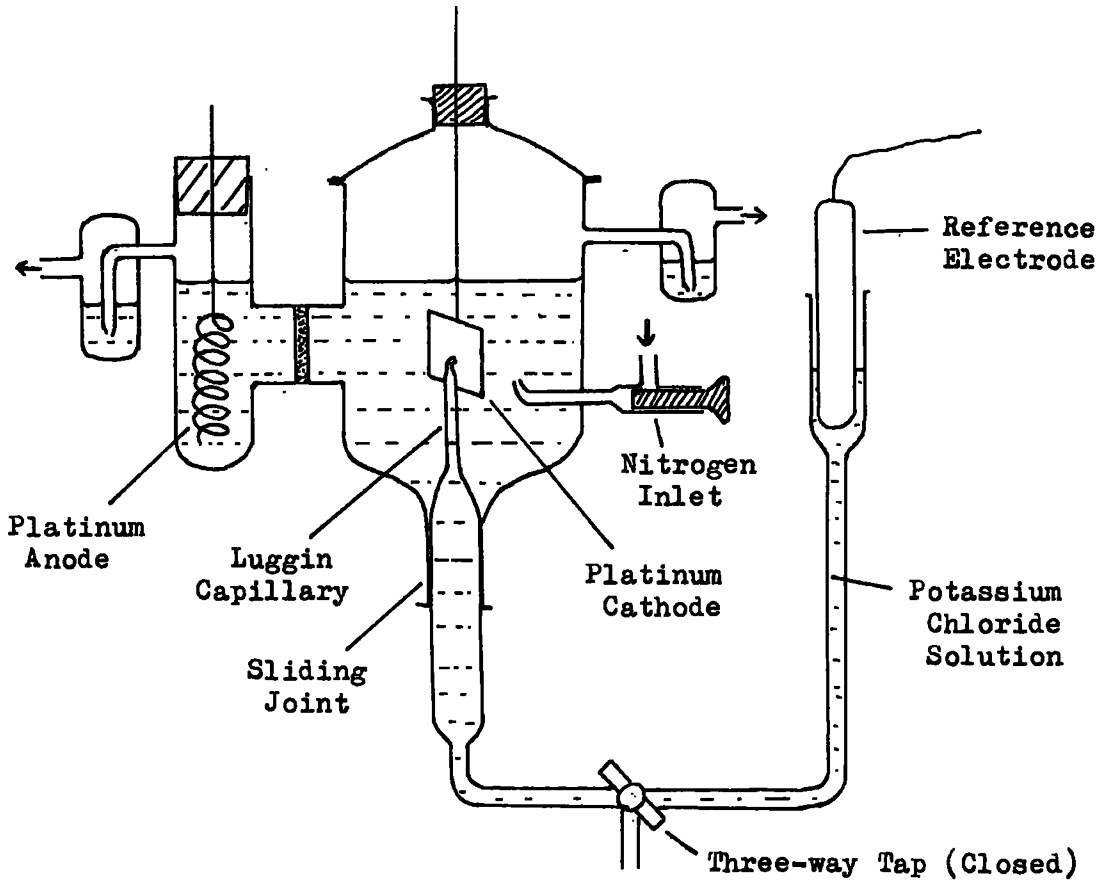
The solutions were 0.35M tetraethylammonium fluoroborate in D.M.F., containing the substrate at 4mM concentration. They were deoxygenated by bubbling dry nitrogen through the cell for 10 to 15 minutes prior to running the voltammograms, and this was also used to stir the solutions between sweeps. Voltammograms were recorded at sweep rates of 4, 10, 20, 40, and 100mV/sec.

Values obtained for the $Ep_{\frac{1}{2}}$'s under identical conditions were reproducible to ± 0.02V.

2. Cyclic Voltammetry

Cyclic voltammetry at higher sweep rates was performed at the E.C.R.C., Capenhurst. The cell used is shown in Figure VI.5.

Figure VI.5 Cell for Cyclic Voltammetry.



The cell had cathode and anode compartments separated by a glass sinter. The cathode was a platinum plate and anode a coiled platinum wire. The reference electrode was a 3.8M KCl calomel electrode (potential +244mV relative to the normal hydrogen electrode, c.f. +242mV for the S.C.E.).

The anode compartment, bubblers, and left-hand arm of the salt bridge were filled with 0.35M T.E.A.F. in D.M.F. The cathode compartment contained this solution with an added 10mM concentration of substrate. The catholyte was deoxygenated with nitrogen, which was also used to effect stirring between runs. Voltammograms were run at 1, 10, 50, 100, & 200 mV/sec and 1 and 10 V/sec, by means of a function generator coupled to a potentiostat. They were recorded on a chart recorder, except for those at over 100mV/sec, when a cathode ray oscilloscope was used and the traces photographed.

CHAPTER VII

EXPERIMENTAL FOR CHAPTER IV

VII.A GENERAL

1. Reagents

Hexafluoropropene and octafluorobut-2-ene were obtained from Bristol Organics Ltd. Tetrafluoroethylene was prepared by vacuum pyrolysis of polytetrafluoroethylene at 580-600°C.[122] The solvents and electrolyte were described on p.80.

2. Apparatus

The H-cell and instrumentation were described on p.80. In addition, an undivided cell was available with a porous carbon cathode, through which the gas was bubbled into the cell. The anode was a piece of nickel plate. Connection between the cathode and the S.C.E. was made via a salt bridge with its tip close to the cathode surface.

The gas to be reduced was frozen down into a trap cooled in liquid air, which was attached to a football bladder serving as a variable volume reservoir. This was connected by a tap to a closed circuit, incorporating the cathode compartment of the cell used. On warming to room temperature, the gas was circulated around this by a peristaltic pump. The circuit included two traps on the outlet from the cell, cooled in an ice/salt bath to prevent volatile liquid products from circulating with the gas.

3. Experimental Procedure

The general procedure was as described on p.83. The gas was circulated through the cell for 30 minutes before performing a potential sweep, in order to produce a saturated solution, and also circulated continuously during the electrolysis. The apparatus ased was only temporary and no attempt was made to recover unreacted gas. The possible conversion was calculated from the charge passed.

After the reaction any volatile products were removed from the traps. The volatiles were removed from the catholyte by transference under vacuum into a cold trap and any D.M.F.-insoluble lower layer separated.

VII.B REDUCTION OF HEXAFLUOROPROPENE

1. In D.M.F.

(a) In H-cell

The reductions in this section were performed in the H-cell on a mercury cathode. The solvent used was D.M.F. (170ml) containing T.E.A.F. (6g).

(i) With 0.0155 Faradays

Hexafluoropropene (9.1g, 60.6 m.moles) was reduced at -1.90V, with an initial current of 270mA. The catholyte started turning cloudy and yellow immediately and became warm as no cooling bath was used. 0.0155 Faradays of charge were passed over a period of 2½ hours, after which the catholyte was brown. This was enough charge to perform a 2-electrons/molecule reduction on 1.16g of hexafluoropropene (44).

The ice/salt traps contained a mixture of volatile fluorocarbons (0.92g). The transferred volatiles from the catholyte yielded a further 0.34g as an insoluble lower layer. G.l.c. with mass spectroscopy (col. O, 35°C) showed this to be a mixture of C_6F_{12} (80) (M^+, 300; 30% by wt.); $C_6F_{13}H$ (86) (no M^+ observed; M^+ - fluorine(19), 301; less than 1% by wt.); C_9F_{18} (81) (three peaks with M^+ = 450, in the ratio 9 : 32 : 59; total 69% by wt.); $C_{12}F_{20}$ (85a) (M^+, 524; less than 1% by wt.). Compounds (80) and (81) were separated by preparative g.l.c. (col. O, room temp.). Compound (80) was shown by ^{19}F n.m.r. to be a mixture of the two dimers (80a) and (80b) obtained by fluoride-ion-induced oligomerisation of (44). (A sample for comparison was donated by Dr.P.L.Russell.) The two largest components of C_9F_{18} (81) had identical g.l.c. retention times with trimers (81a) and (81b) obtained by fluoride ion reaction at room temperature.

The D.M.F. from the catholyte was shown by g.l.c./mass spectroscopy to contain traces of $C_6F_{13}H$ (86) (ca. 0.2g) and C_3F_7H (87) (M^+ - F, 151).

Extraction of the involatile residue from the catholyte with methylene chloride, washing, drying, and removal of the solvent by distillation, yielded a brown tar (1.70g). This was molecularly distilled under reduced pressure (0.05mm) at up to 170°C, to give a yellow oil (0.81g), shown by g.l.c. (col. O, 170°C) to be a multicomponent mixture. Its i.r. spectrum showed C-H stretch at 2860 and 2970 cm^{-1} and broad C-F stretching vibrations between 1370 and 1000 cm^{-1}. Three bands appeared in the double bond region at 1760, 1700 and 1660 cm^{-1}. Elemental analysis gave C, 30.5; H, 2.5; N, 0.9; and F, 48.8%.

(ii) With 0.0040 Faradays

In a similar reaction to the above, only 0.0040 faradays of charge were passed (2 electrons/molecule for 0.30g of (44)), over a period of 20 mins. The gas was then circulated for a further 8 hours with no current and 3.15g of volatile liquid was obtained. This was shown by g.l.c. to contain C_6F_{12} (40%); $C_6F_{13}H$ (5%); C_9F_{18} (47%); and $C_{12}F_{20}$ (8%). The trimers C_9F_{18} contained mainly (81a) and (81b), with only a trace of (81c). The D.M.F. contained traces of $C_6F_{13}H$ and C_3F_7H. Only a trace of involatile product was obtained.

(iii) Control Experiment with no Current

Hexafluoropropene (44) (4.0g, 26.6 m.moles) was circulated through a flask containing D.M.F. (30ml), T.E.A.F. (2.3g) and mercury (33g), for 10 hours at room temperature. 3.8g of (44) was recovered and no oligomers were produced.

(iv) In the Presence of Boron Trifluoride Diethyletherate

Boron trifluoride diethyletherate (2.70g, 19.0m.moles) was added to the catholyte and gave a current of 156mA at -1.90V. After bubbling hexafluoropropene (44) this only increased to 210mA. 0.0232 Faradays were passed (2 electrons/molecule for 1.74g of (54)) to give a brown solution. During the electrolysis no oligomers started to collect in the traps for some time but, finally, 1.61g were obtained. G.l.c. showed this mixture to contain C_6F_{12} (7%); $C_6F_{13}H$ (1%); C_9F_{18} (90%); and $C_{12}F_{20}$ (2%). Extraction of the involatile residue yielded a brown tar (1.70g), which gave only a trace of material on molecular distillation under reduced pressure.

(b) On Porous Carbon Cathode

The reductions described in this section were performed using the porous carbon cathode, through which the gas was bubbled into the cell.

(i) Undivided Cell

Hexafluoropropene (44) was reduced at -2.0V in the one-compartment cell, with an initial current of 190mA. 0.00990 Faradays were passed (2 electrons/molecule for 0.74g of (44)) and the gas bubbled for several hours afterwards, giving a brown solution. A total of 1.98g of volatile oligomers was obtained, shown by g.l.c. to contain C_6F_{12} (24%); $C_6F_{13}H$ (12%); C_9F_{18} (60%); and $C_{12}F_{20}$ (2%). The D.M.F. was refluxed up a fractionating column under reduced pressure to liberate a gaseous product (ca. 1.5g), which was trapped in liquid air. G.l.c./mass spectroscopy showed this to be the compound C_3F_7H (87) observed previously. It was identified from its n.m.r. spectra, run in $CDCl_3$ soln. in a sealed n.m.r. tube; as 2-H-heptafluoropropane.[94] (^{19}F and ^{1}H n.m.r. spectra No.6; i.r. spectrum No.7).

The involatile residue from the reaction mixture was extracted with ether, washed, dried ($MgSO_4$), and the solvent distilled off, to give a brown tar (0.83g), which yielded only a trace of material on molecular distillation under reduced pressure.

(ii) Divided Cell

The nickel anode of the undivided cell was enclosed in a glass sleeve with a sinter to allow contact with the cathode compartment. This made it into a divided cell with a very unsatisfactory cell geometry.

Hexafluoropropene (44) was reduced at -2.0V, with an initial current of 96mA. 0.00894 Faradays were passed (2 electrons/molecule for 0.67g of (44)). A total of 3.53g of volatile fluorocarbons was obtained, containing C_6F_{12} (19%); $C_6F_{13}H$ (1.5%); C_9F_{18} (77%); and $C_{12}F_{20}$ (2.5%). Only a small amount of C_3F_7H was present in the D.M.F. The involatile residue yielded 1.49g of tar on solvent extraction.

2. In Aqueous D.M.F.

Hexafluoropropene (44) (6.9g, 45.9 m.moles) was reduced at -2.10V in the H-cell, using an electrolyte solution containing 2½% water by volume. 0.0119 Faradays were passed (2 electrons/molecule for 0.89g of (44)), turning the catholyte orange. No volatile fluorocarbon liquid was obtained. Refluxing the D.M.F. under reduced pressure, trapping gaseous products in liquid air, gave 2-H-heptafluoropropane (87) (1.97g, 11.57m.moles).

The involatile residue was extracted with methylene chloride, washed, dried, and the solvent distilled off, to give a brown residue (0.58g). On attempted molecular distillation under reduced pressure, this appeared to start to decompose at 140°C. It was heated to 175°C, while pumping the volatiles into a trap in liquid air, giving a liquid in two layers (ca. 0.3g) and a black residue (0.28g). Both layers of the liquid were shown by g.l.c. to be multicomponent mixtures.

VII.C REDUCTION OF OCTAFLUOROBUT-2-ENE

Octafluorobut-2-ene (77) (12.5g, 62.5 m.moles) was reduced in the H-cell at -1.90V, with an initial current of 210mA. 0.0226 Faradays of electricity was passed (2 electrons/molecule for 2.26g of (77)), turning the catholyte brown. The ice/salt traps contained a liquid (0.13g), and a further 0.83g was obtained from the volatiles from the catholyte, as an insoluble lower layer. This was shown by g.l.c./mass spectroscopy (col. O, 70°C) to be a mixture of C_8F_{14} (83) (M^+, 362; 12% by wt.); C_8F_{16} (82) (M^+ - F, 381; 80% by wt.); and $C_{12}F_{22}$ (84) (M^+ - F, 543; 8% by wt.). Compound (82) had an identical mass spectrum and g.l.c. retention time with that of a mixture of cis and trans isomers produced by fluoride-ion-induced dimerisation of (77) (from I.C.I.).

Extraction of the involatile residue with methylene chloride, washing, drying ($MgSO_4$), and distillation of the solvent, gave a brown tar (1.83g). Molecular distillation under reduced pressure (0.05mm) at 150°C, yielded an orange oil (0.37g), shown by g.l.c. (col. O, 150°C) to contain several components. Its i.r. spectrum contained both C-H and C-F stretching vibrations.

VII.D REDUCTION OF TETRAFLUOROETHYLENE

1. In Anhydrous D.M.F.

Tetrafluoroethylene (22) (5.7g, 57.0 m.moles) was reduced at -2.20V in the H-cell. 0.0133 Faradays were passed (2 electrons/molecule for 0.67g of (22)), giving a brown solution. The traps were empty, and only 0.09g of insoluble lower layer was obtained from the volatiles from the catholyte. This was shown by g.l.c./mass spectroscopy to contain one major component (highest $^m/e$: 459), which could not be identified. The involatile residue was extracted with methylene chloride, washed, dried, and the solvent distilled off, to give a brown residue (0.53g), which could not be sublimed under reduced pressure or decolourised with charcoal.

2. In Aqueous D.M.F.

Tetrafluoroethylene (22) (5.3g, 53.0 m.moles) was reduced at -2.40V in the H-cell, using D.M.F. containing 2½% water as the solvent. 0.0132 Faradays were passed (2 electrons/molecule for 0.66g of (22)), giving a yellow solution. No volatile oligomers collected in the traps and no insoluble lower layer was obtained from the catholyte. The volatiles were refluxed under reduced pressure and a gaseous product trapped in liquid air (0.83g). This was shown by g.l.c./mass spectroscopy to be a mixture of pentafluoroethane (<u>90</u>) (M^+, 120; ca. 85%); and an unidentified component (highest $^m/e$: 98). The i.r. spectrum (No.8) showed only absorptions due to (<u>90</u>).[95] When this gas was sealed in an n.m.r. tube it was lost when the tube burst. Extraction of the involatile residue from the catholyte yielded only a trace of tar.

CHAPTER VIII

EXPERIMENTAL FOR CHAPTER V

VIII.A GENERAL

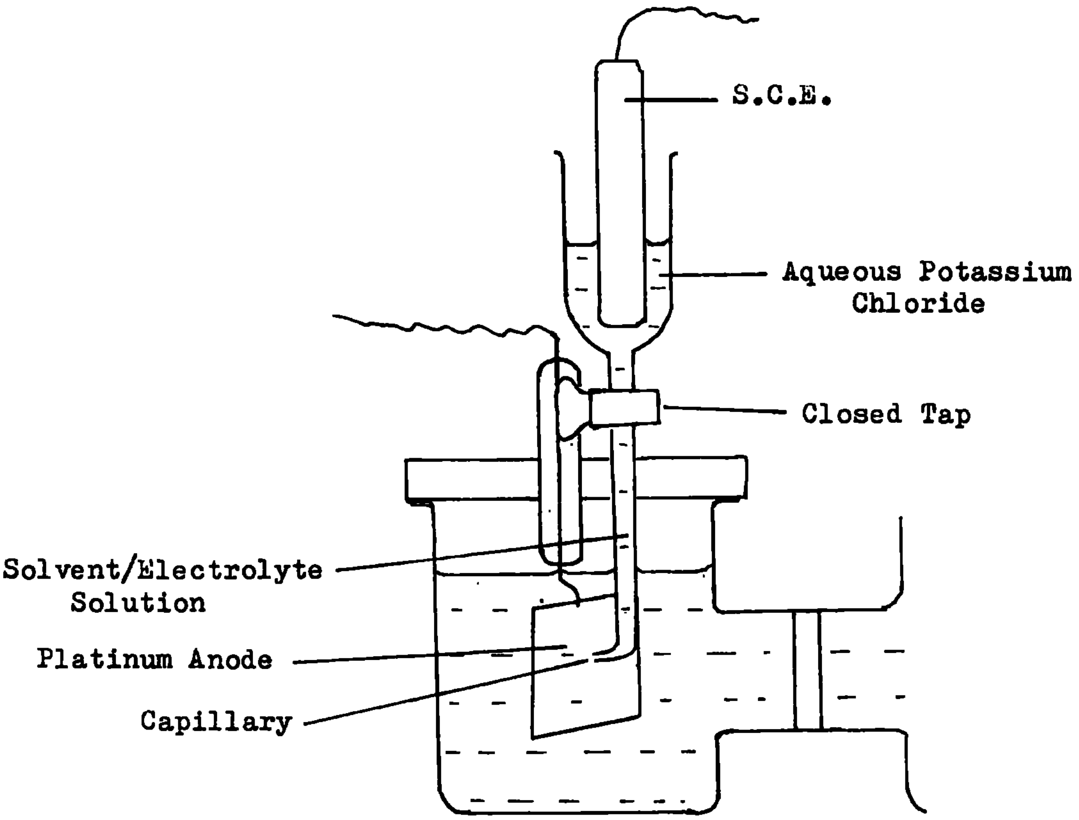
1. Reagents

The methoxy-derivatives were prepared by nucleophilic substitution reactions with methoxide ion on the corresponding polyfluorobenzenes by published routes.[123-125]

The acetonitrile and tetraethylammonium fluoroborate (T.E.A.F.) were as described in Chapter VI. Acetic acid was Analar and used untreated. Sodium acetate was dried by alternately heating to 150°C under vacuum and crushing to a fine powder, and stored under dry nitrogen.

2. Apparatus and Experimental Procedure

The apparatus and experimental procedure were as described in Chapter VI, with the exception that the H-cell was used with a platinum cathode and connection between the anode and the S.C.E. was made via a salt bridge, adapted from a dropping funnel:



The potentiostat was used in its oxidation mode, with the switch marked with '+' and '-' set to the '-' position, (see Fig. VI.2, p.82).

VIII.B OXIDATIONS IN ACETONITRILE

1. 2,3,5,6-Tetrafluoroanisole (110)

2,3,5,6-Tetrafluoroanisole (110) (4.68g, 26.0 m.moles) was oxidised at + 2.40V in a solution of T.E.A.F. (12g) in acetonitrile (170ml). 0.0131 Faradays of charge were passed (0.50 electrons/molecule), turning the anolyte orange. The anolyte was added to ether and washed many times with water to remove acetonitrile. The ethereal extracts were dried ($MgSO_4$) and the ether removed by distillation. The final fraction was removed by transference under vacuum into a cold trap, giving a colourless liquid (5.71g), shown by g.l.c. (col. O, 130°C) to contain ether and (110) (ca. 2.30g). The cream-coloured solid residue (1.84g) was sublimed under reduced pressure (0.05mm, 100°C), to give a white sublimate identified as octafluoro-4,4'-dimethoxybiphenyl (113) (1.53g, 65% C.E.), m.p. 82.5-84.5°C (lit.[126] 83-84.5°C). (Found: C, 47.2; H, 1.4; F, 42.0%; M^+, 358. Calc. for $C_{14}H_6F_8O_2$: C, 47.0; H, 1.7; F, 42.4%; M, 358). λ_{max}(cyclohexane) 244nm (ε 18,300); ^{19}F and ^1H n.m.r. spectra No.7; i.r.spectrum No.9.

2. 2,3,6-Trifluoroanisole (112)

2,3,6-Trifluoroanisole (112) (3.74g, 23.1 m.moles) was oxidised at + 2.10V, with passage of 0.0115 faradays of charge (0.50 electrons/molecule). The orange anolyte was treated as above to give a brown solid residue (0.85g) and g.l.c. showed the presence of ca. 2.13g of (112) in the volatiles. The solid was sublimed under reduced pressure (0.05mm, 100°C) to give a cream-coloured sublimate, identified as hexafluoro-2,2'-dihydro-4,4'-dimethoxybiphenyl (114) (0.48g, 26% C.E.), m.p. 124-125°C (from petroleum ether, 60-80° fraction) (lit.[115] 125-126°C). (Found: C, 52.0; H, 2.9; F, 34.9%; M^+, 322. Calc. for $C_{14}H_8F_6O_2$: C, 52.2; H, 2.5; F, 35.4%; M, 322). λ_{max}(cyclohexane) 248nm (ε 18,000), 273nm (s)

(ε ca. 8,300); n.m.r. spectrum No.8; i.r. spectrum No.10.

3. 2,4,5-Trifluoroanisole (111)

2,4,5-Trifluoroanisole (111) (3.24g, 20.0 m.moles) was oxidised at + 2.20V, with passage of 0.0098 faradays (0.49 electrons/molecule). The brown anolyte was treated as previously to give a brown solid residue (0.34g), which yielded no material on sublimation at up to 170°C under reduced pressure. The aqueous phase was also brown. G.l.c. showed the volatiles to contain ca. 2.11g of (111).

4. Pentafluoroanisole (109)

(a) 0.70 Electrons/Molecule

Pentafluoroanisole (109) (2.0g, 10.1 m.moles) was oxidised at + 2.40V in a solution of T.E.A.F. (6g) in acetonitrile (170ml). 0.0070 Faradays were passed (0.70 electrons/molecule), giving an orange solution. The volatiles were removed from the anolyte by transference under vacuum into a cold trap and g.l.c. estimation (col. O, 110°C) showed them to contain (109) (ca. 1.2g). The involatile residue was added to water and extracted well with ether. The extracts were washed, dried ($MgSO_4$), and the solvent distilled off to leave an orange/brown residue, which on molecular distillation under reduced pressure (0.05mm, 100°C) gave a yellow liquid (0.21g). This was shown by g.l.c. to be very similar to the red liquid obtained in the next section. The aqueous phase from the extraction above was brown and highly acidic. It was neutralised with sodium hydroxide solution and re-extracted but yielded no further material.

(b) 1.22 Electrons/Molecule

Pentafluoroanisole (109) (2.96g, 14.9 m.moles) was oxidised as above, with passage of 0.0182 faradays of charge (1.22 electrons/molecule), giving a dark orange solution. The volatiles were removed by transference under vacuum into a cold trap and the residue extracted with methylene chloride and water. The aqueous layer was again brown and highly acidic. The methylene chloride extracts were washed well, dried, and the solvent distilled off. Molecular distillation of the residue (0.05mm, 100°C) gave a viscous red liquid (0.83g) and an intractible brown residue (0.37g).

G.l.c. analysis of the red liquid (col. O, 170°C) showed it to be a mixture of two components A and B. On diluting it in ether before performing a preparative-scale g.l.c. separation, the trace changed, with a new, more volatile component C appearing and A and B merging to give one peak D. These were separated by preparative g.l.c. to give a white solid C (0.13g) and a yellow liquid D (0.30g).

The solid C had a mass spectral M^+ at 184 (C_6F_5OH) and a breakdown pattern consistent with pentafluorophenol (115).

The liquid D was shown by g.l.c. to contain C, A and B and g.l.c. with mass spectroscopy showed their parent peaks to be at 184, 184 and 217 respectively. There were minor differences in the breakdown patterns of C and A.

VIII.C ATTEMPTED ACETOXYLATIONS

1. Pentafluoroanisole (109) in Acetonitrile/Acetic Acid/T.E.A.F.

(a) Without Neutralisation of Reaction Mixture

Pentafluoroanisole (109) (3.07g, 15.5 m.moles) was oxidised at + 2.40V in a solution of T.E.A.F. (12g) in a 3 : 1 mixture by volume of acetonitrile and acetic acid (170ml). 0.0248 Faradays were passed (1.60 electrons/molecule). The yellow anolyte was added to a large excess of water and extracted well with ether. The extracts were dried and the ether distilled off. The final volatile fraction was removed by transference under vacuum into a cold trap and shown by g.l.c. to be a mixture of acetonitrile, acetic acid and (109) (ca. 1.0g). The residue was a viscous brown liquid. On attempting to molecularly distil this under reduced pressure (0.05mm, 100°C), it decomposed and the pressure rose.

On pumping at 100°C an orange sublimate was obtained (0.40g), identified after recrystallisation from CCl_4 had given a yellow solid as an impure sample of methoxytrifluoro-p-benzoquinone (<u>117</u>) (17% C.E., assuming 2 electrons/molecule). Its mass spectrum showed the correct M^+ at 192 and an impurity at 194. Its n.m.r. spectrum agreed closely with that of (<u>117</u>),[118] showing multiplets at 143.5 and 152.7ppm in the ratio of 2 : 1 in its ^{19}F spectrum.(Run on the Brüker spectrometer in $CDCl_3$ solution, with shifts measured relative to internal $CFCl_3$). Its ^1H n.m.r. spectrum showed a doublet at 4.36ppm (J = 5Hz) relative to external T.M.S. The sample deteriorated rapidly in the atmosphere, giving off a pungent gas,(probably HF). No satisfactory elemental analysis was obtained.

(b) Treating the Reaction Mixture with Sodium Carbonate

(i) 1.39 Electrons/Molecule

Pentafluoroanisole (<u>109</u>) (3.33g, 16.8 m.moles) was oxidised as above, with passage of 0.0233 faradays of charge (1.39 electrons/molecule). The yellow anolyte was added to sodium carbonate solution and extracted with ether. The extracts were washed, dried,and the solvent removed by transference under vacuum into a cold trap. G.l.c. estimation showed them to contain (<u>109</u>) (ca. 1.38g). The residue was a yellow oil (1.80g), which showed a large number of ^1H and ^{19}F signals in its n.m.r. spectrum. Elemental analysis gave C, 39.8; H, 3.4; F, 24.5%. G.l.c. (col. O, 160°C) showed it to contain a large number of components. It appeared to be unstable in the air, giving off pungent fumes. Molecular distillation of a sample (0.71g) under reduced pressure (0.05mm, 100°C) gave an orange liquid (0.34g), shown by g.l.c. to be a multicomponent mixture. Its mass spectrum showed a number of small peaks at up to $^m/e$ 432. Large peaks were present at 85, 74, 62, and 47 and the base peak was 43 (CH_3CO).

Re-acidification of the aqueous phase and ether extraction gave only 0.08g of brown tar.

(ii) 0.57 Electrons/Molecule

Pentafluoroanisole (109) (2.60g, 13.1 m.moles) was oxidised as before, with passage of 0.0075 faradays (0.58 electrons/molecule). The reaction mixture was treated as before to give a yellow oil (0.28g) similar to that obtained previously. G.l.c. estimation of the volatiles indicated the presence of (109) (ca. 1.8g).

2. 2,3,5,6-Tetrafluoroanisole (110)

(a) In Acetonitrile/Acetic Acid/T.E.A.F.

2,3,5,6-Tetrafluoroanisole (110) (3.09g, 17.2 m.moles) was oxidised at + 2.40V in the electrolyte solution used above. 0.0209 Faradays were passed (1.21 electrons/molecule). The reaction mixture was treated as above to give a yellow oil (1.21g) and g.l.c. on the volatiles showed the presence of (110) (ca. 1.42g). The oil showed a large number of ^1H and ^{19}F signals in its n.m.r., the largest ^{19}F peaks being due to the dimer (113). G.l.c. (col. O, 130°C) showed a large number of components. On attempted molecular distillation under reduced pressure (0.05mm, 100°C) it decomposed and the pressure rose but all that collected on the cold finger was a sticky tar (0.53g).

(b) In Acetonitrile/Acetic acid/T.E.A.F./Sodium Acetate

The electrolyte solution used above was shaken with sodium acetate to give a saturated solution and this gave a current of 272mA at + 2.40V. On addition of 2,3,5,6-tetrafluoroanisole (110) (8.49g, 47.1 m.moles) there was no increase in current. 0.0190 Faradays were passed (0.40 electrons/molecule of (110)). The yellow anolyte was treated as before to give a deep orange oil (1.44g). The volatiles contained 6.47g of (110) by g.l.c. G.l.c. showed the oil to contain a large number of components. It decomposed during molecular distillation and some of the gas produced was trapped but could not be identified. Its mass spectrum showed M^+ at 96 and its ^{19}F n.m.r. spectrum showed a multiplet at 131.9ppm.

PART II

NOVEL REARRANGEMENTS OF PYRIDAZINE DERIVATIVES

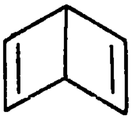
DISCUSSION

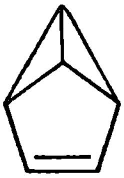
CHAPTER IX

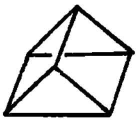
NOVEL REARRANGEMENTS OF PYRIDAZINE DERIVATIVES

IX.A INTRODUCTION

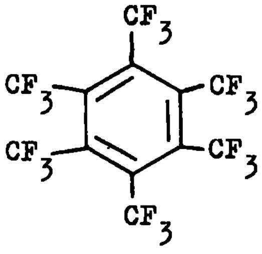
In recent years a large number of valence bond isomers of aromatic systems have been isolated, such as Dewar benzenes (120), benzvalenes (121), and prismanes (122), which had previously been thought of as very unlikely structures. These have mainly been prepared by photolysis of aromatic systems and this subject has recently been reviewed.[127] The intermediacy of valence bond isomers has also been postulated in many cases to explain rearrangements of aromatic rings.


(120)

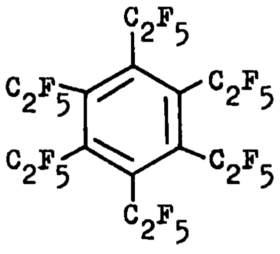

(121)


(122)

As might be anticipated, these valence isomers are normally very unstable with respect to rearomatisation but it has been found that various perfluoroalkyl derivatives are both more easily formed and of higher thermal stability than their hydrocarbon analogues. The most stable valence isomers isolated have been obtained by irradiation of hexakis-trifluoromethyl benzene (123) and hexakispentafluoroethyl benzene (124) in the gas phase or solution.[128-130] The Dewar benzene derived from (124) can also be obtained by pyrolysis of (124) and this was the first example of a thermal rearrangement giving a valence isomer.[131]

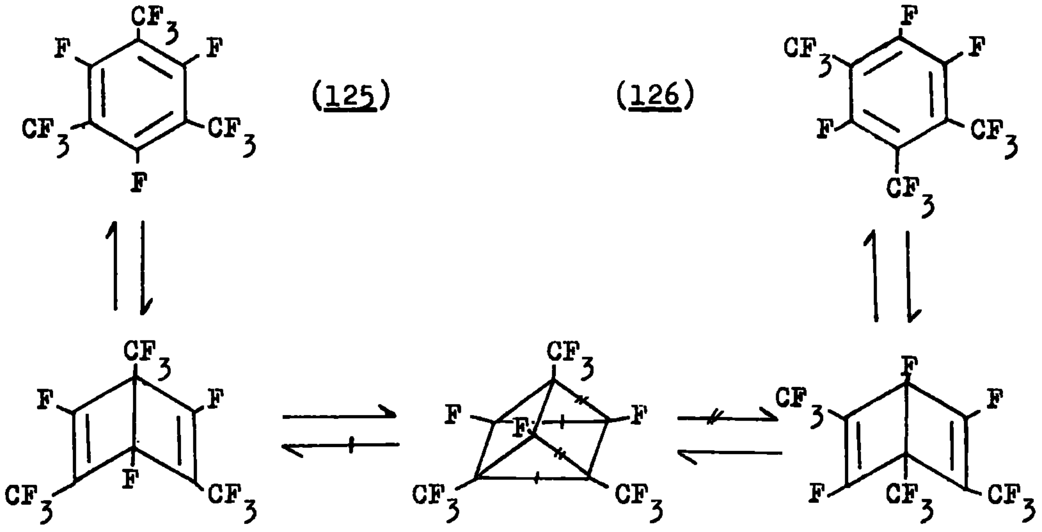


(123)



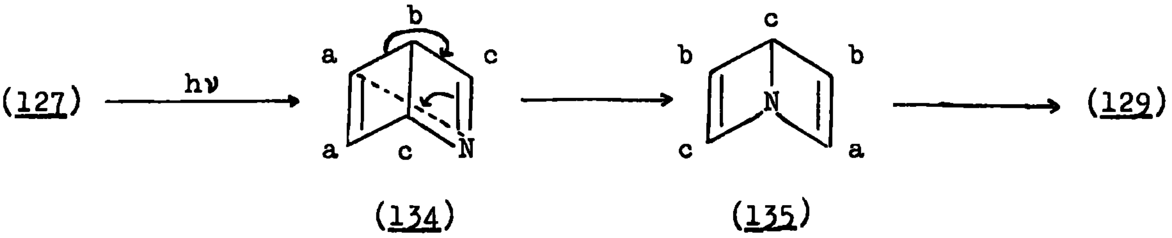
(124)

Scheme IX.1

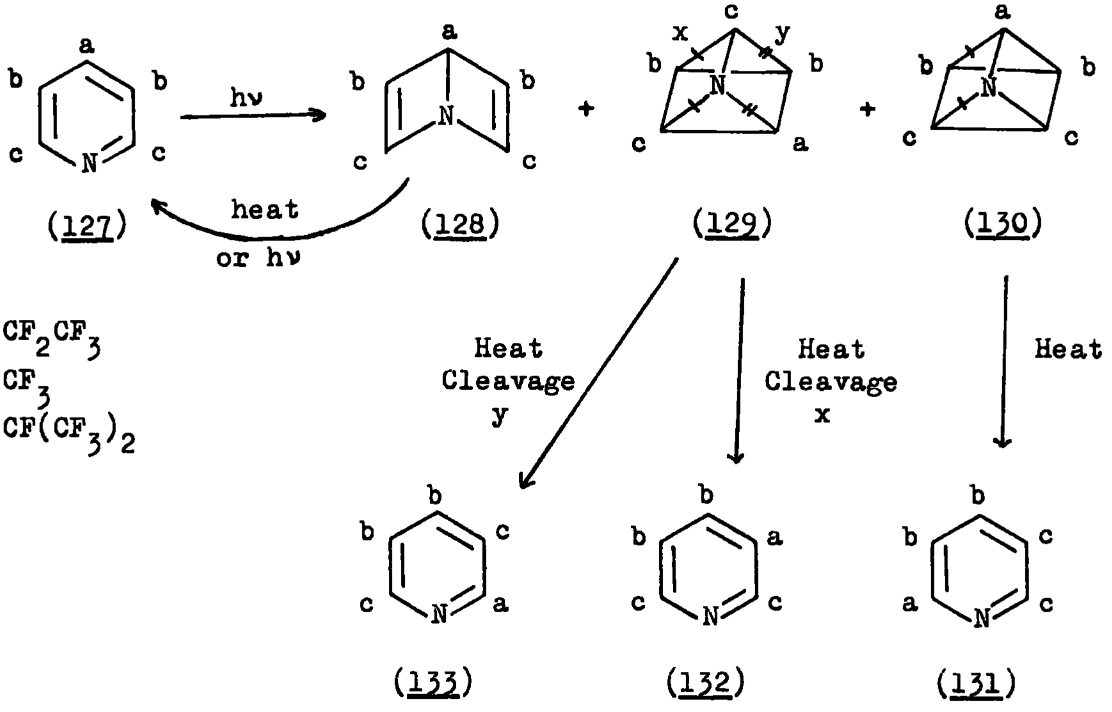


Perfluoro-1,3,5- and -1,2,4-trimethylbenzenes (125) and (126) can be interconverted photochemically, via the route shown in Scheme IX.1. This provides an example of a skeletal rearrangement where the intermediacy of valence isomers has been demonstrated by the isolation of the Dewar and prismane isomers as moderately stable species.[132]

In these laboratories there has been a considerable programme of investigation of the skeletal rearrangements of perfluorinated aza-aromatics. For example, the photolysis of the pyridine derivative (127) gives the para-bonded species (128) and the two azaprismanes (129) and (130), which give the pyridines (131), (132) and (133) on thermal rearomatisation.[133] (See Scheme IX.2 overleaf). The unsymmetrical azaprismane (129) is thought to be formed via the formation of the para-bonded species (134), which rearranges to (135) prior to cyclisation, although neither of these species have been isolated.



Scheme IX.2

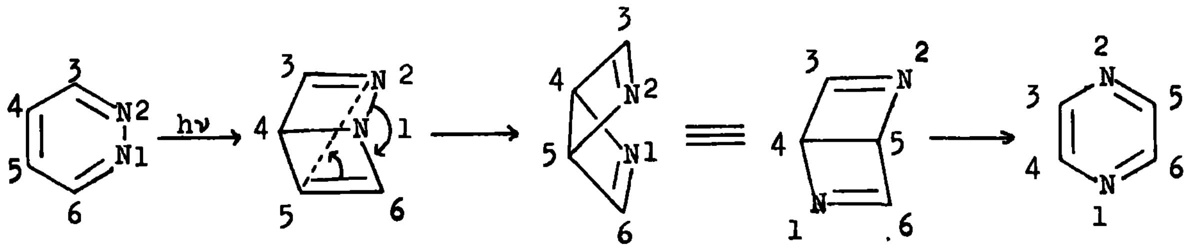


a = CF_2CF_3
b = CF_3
c = $CF(CF_3)_2$

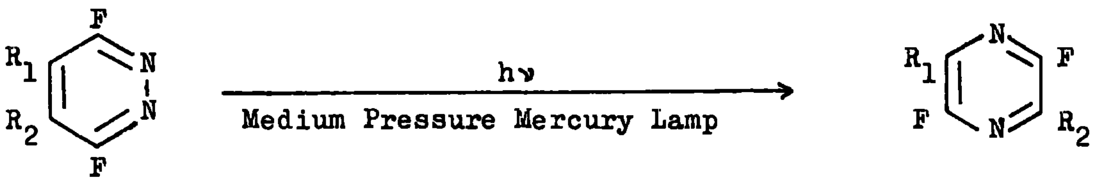
Previous Work on the Rearrangement of Pyridazine Derivatives

1. Photolysis

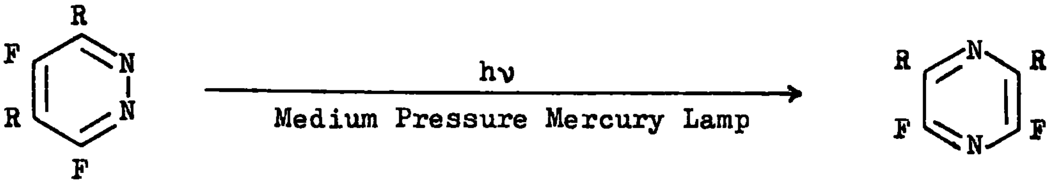
The photolysis of the perfluoroalkylpyridazine derivatives (136) - (144) in the vapour phase produces a 1,3-shift in the relative position of the nitrogen atoms, to give the pyrazine derivatives (145) - (153), (Scheme IX.3 overleaf).[134] Prior to this work, 1,3 transpositions in aromatic rings were believed to occur via prismane-type intermediates or successive 1,2-shifts[135,136] but these mechanisms could not explain the highly specific positions of the substituent groups in the pyrazines. However, it has now been shown that a para-bonded species (154) is formed, followed by rearrangement to (155) prior to rearomatisation. By irradiating the



Scheme IX.3



(136)	$R_1 = R_2 = F$	(145)
(137)	$R_1 = CF(CF_3)_2$, $R_2 = F$	(146)
(138)	$R_1 = R_2 = CF(CF_3)_2$	(147)
(139)	$R_1 = CF_2CF_3$, $R_2 = F$	(148)
(140)	$R_1 = R_2 = CF_2CF_3$	(149)
(141)	$R_1 = CF(CF_3)CF_2CF_3$, $R_2 = F$	(150)
(142)	$R_1 = R_2 = CF(CF_3)CF_2CF_3$	(151)

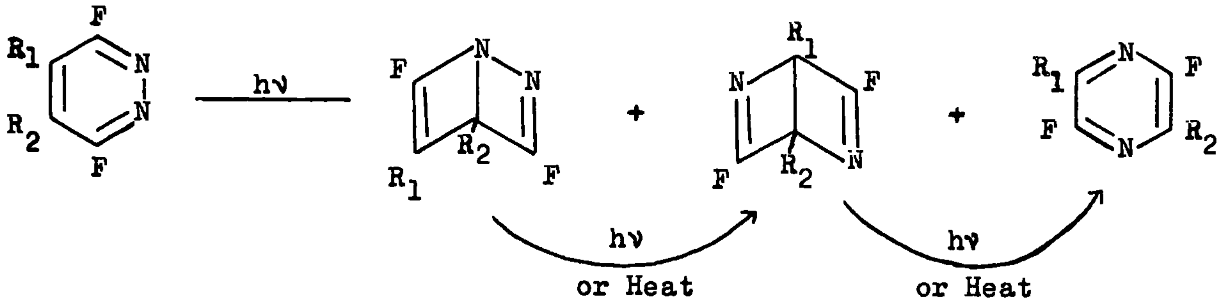


(143)	$R = CF(CF_3)_2$	(152)
(144)	$R = CF(CF_3)CF_2CF_3$	(153)

pyridazines (136) - (142) at 254 or 300nm in an apparatus where the products are removed from the irradiation zone by transference through the zone,under vacuum, into a cold trap, one or both of the intermediates corresponding to (154) and (155) can be isolated.[137] (See Scheme IX.4 overleaf).

Recently, another group has prepared perfluoro-3,6-trimethylpyridazine (156) and successfully rearranged it to the pyrazine (157) by photolysis in the vapour phase.[138] This is the first 3,6-bisperfluoroalkyl derivative to be rearranged in this way and the product is in agreement with the above mechanism.

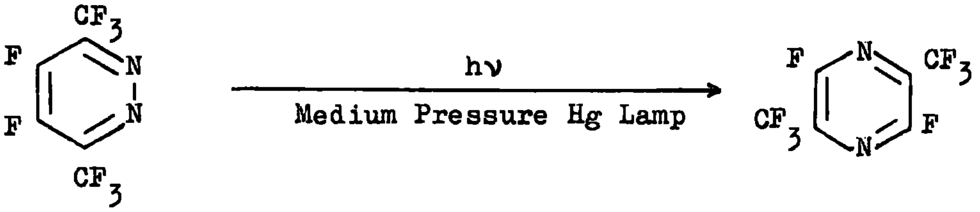
Scheme IX.4



(138)	(138a)	(138b)	(147)
(142)	(142a)	(142b)	(151)
(136)†	*	(136b)	(145)
(137)	*	(137b)	(146)
(139)	*	(139b)	(148)
(140)	*	(140b)	(149)
(141)	*	(141b)	(150)

* Not isolated.

† Irradiated in a static system



(156)

(157)

These rearrangements do not all occur equally easily. Under identical conditions it is significantly easier to rearrange perfluoro-4,5-di-isopropylpyridazine (138) than the 3,5-isomer (143).[134] Furthermore it has not been possible to rearrange perfluoro-3,4,6-tri-isopropylpyridazine, perfluorotetraphenylpyridazine, various perfluoroalkylphenyl derivatives with substituents in either the 4,5- or ortho positions, or perfluorotetraethylpyridazine.

The reactions do not appear to involve triplet states or be mercury sensitised, as neither addition of oxygen nor rigorous exclusion of mercury has any effect.

2. Pyrolysis

The pyrolysis of perfluorotetraphenylpyridazine (158) and the perfluorodialkyldiarylpyridazines (159) - (161) results in the elimination of nitrogen, to give the acetylenes (162) - (165).[139]

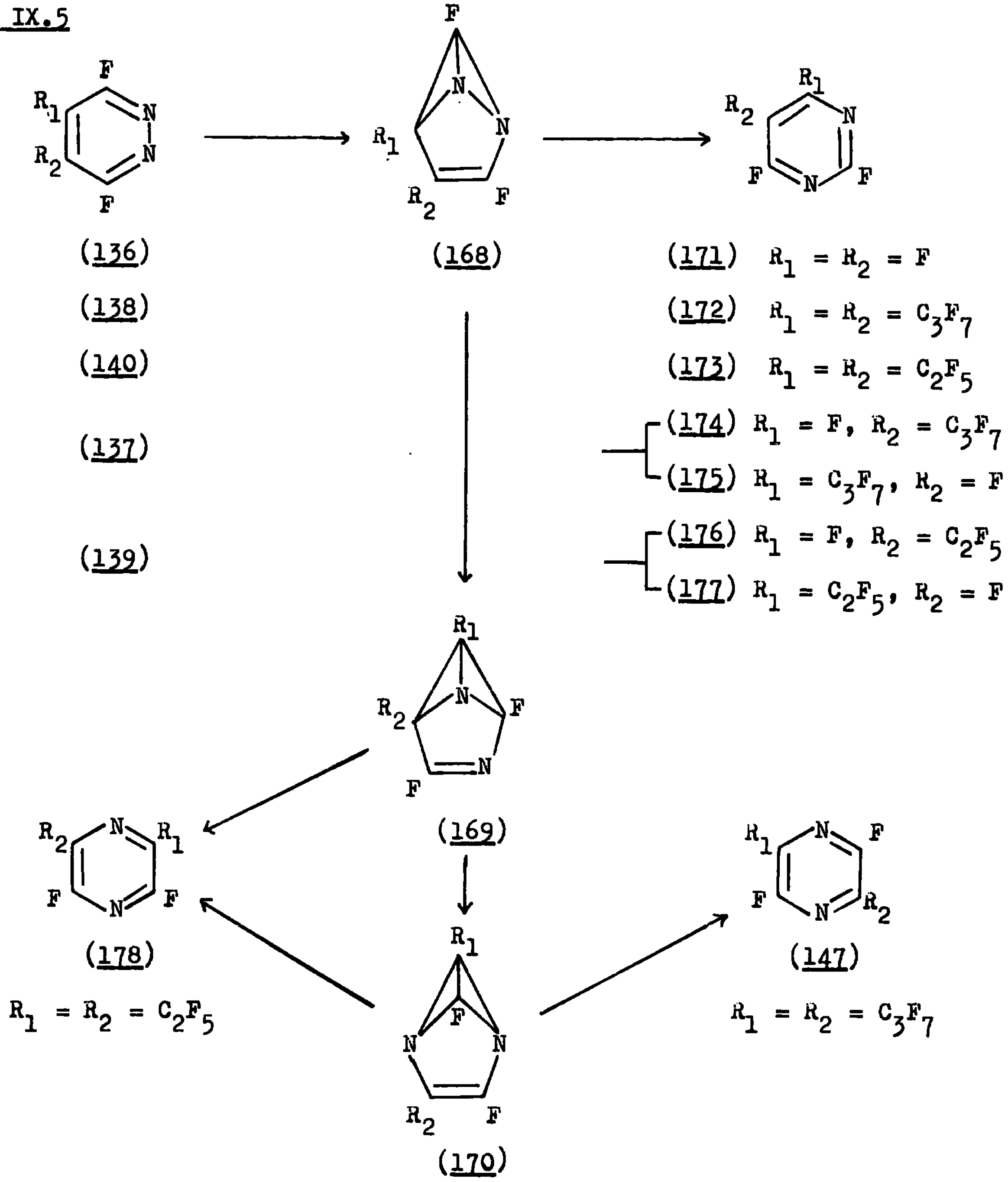
Temperature				Yield
725°C	(158)	$X = Y = C_6F_5$	(162)	90%
720°C	(159)	$X = CF_2CF_3$, $Y = C_6F_5$	(163)	88%
680°C	(160)	$X = CF(CF_3)_2$, $Y = C_6F_5$	(164)	84%
700°C	(161)	$X = CF(CF_3)_2$, $Y = 4\text{-}C_5F_4N$	(165)	82%

The temperatures quoted are those required for pyrolysis under vacuum but the same products are obtained at lower temperatures using flow conditions at atmospheric pressure. Tetrachloropyridazine (166) also loses nitrogen, giving mainly hexachlorobutadiene and chlorine, with a large number of minor products. 4,5-Dichlorodifluoropyridazine (167) gives a complex mixture, from which no identifiable products have been isolated.

In contrast to these results, however, the flow pyrolysis of tetrafluoropyridazine (136)[140] and a number of perfluoro-mono- and di-alkylpyridazines[141] produces a 1,2-shift in the relative position of the nitrogen atoms, giving pyrimidine derivatives as the major products. (See Scheme IX.5).

The positions of the substituents in the pyrimidine products is best explained by the intermediacy of the diazabenzvalene (168). Thus, a perfluoro-4-alkyl-pyridazine can give a benzvalene with the alkyl group

Scheme IX.5



(136) (138) (140) (137) (139)

(168)

(171) $R_1 = R_2 = F$

(172) $R_1 = R_2 = C_3F_7$

(173) $R_1 = R_2 = C_2F_5$

(174) $R_1 = F$, $R_2 = C_3F_7$

(175) $R_1 = C_3F_7$, $R_2 = F$

(176) $R_1 = F$, $R_2 = C_2F_5$

(177) $R_1 = C_2F_5$, $R_2 = F$

(169)

(178) $R_1 = R_2 = C_2F_5$

(170)

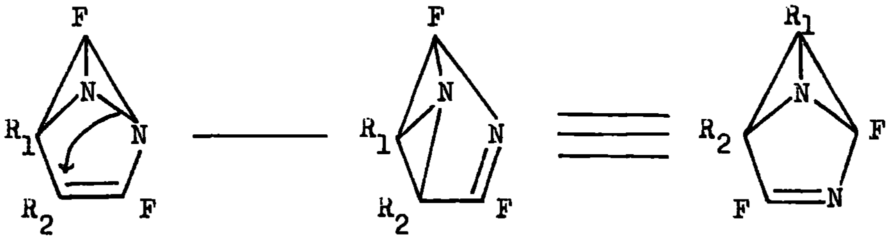
(147) $R_1 = R_2 = C_3F_7$

at either of the positions occupied by R_1 and R_2 in (168). Rearomatisation would give a mixture of 4- and 5-substituted pyrimidines and this is observed in the rearrangement of perfluoro-4-ethylpyridazine (139) and -4-isopropylpyridazine (137).

Perfluoro-4,5-diethylpyridazine (140) gives a small yield of the pyrazine (178), which can be explained by rearrangement of the diazabenzvalene (168) to (169) prior to rearomatisation. The perfluoro-

4,5-di-isopropyl compound (138), however, gives the 2,5-pyrazine derivative (147), for which the rearrangement of (169) to (170) must be postulated. The diazabenzvalene (170) could also rearomatise to give a 2,6-pyrazine analogous to (178), however. This difference between the two disubstituted compounds has been attributed to an increased driving force to separate the perfluoroalkyl groups in (169) as they are increased in size.

The rearrangements of the diazabenzvalene intermediates (168) → (169) → (170) are, in effect, 1,3 group migrations:



(168) (169)

According to orbital symmetry rules these are thermally disallowed suprafacial processes but the rules do not strictly apply to unsymmetrical species such as these. When nitrogen is present there is no necessity even for the same electron pair to be used in the formation of the new bond, as the nitrogen lone pair may be involved.

An alternative mechanism involving the formation of diazabicyclopropenyls and subsequent Cope rearrangements was ruled out, as there would be no apparent reason for the specific substituent labelling observed in the products.

Bimolecular processes are unlikely because pyrimidines and pyrazines are still formed during pyrolyses under vacuum conditions. These conditions require higher temperatures, however, and fragmentation products constitute a major proportion of the mixture.

Like the photochemical rearrangements, the thermal rearrangements do not all occur equally readily. In the atmospheric pressure, flow pyrolyses the di-isopropyl compound (138) requires a temperature of 550°C, compared to 650°C for the di-ethyl compound (140) and 815°C for tetrafluoropyridazine (136). Compound (138) can be successfully rearranged at the much lower temperature of 300°C, however, by prolonged heating in a sealed nickel tube, when the pyrimidine (172) is the sole product. Perfluoro-3,5-di-isopropylpyridazine (143), perfluoro-3,4,6-tri-isopropylpyridazine, and perfluorotetraphenylpyridazine (158) are unchanged under these conditions at up to 380°C.

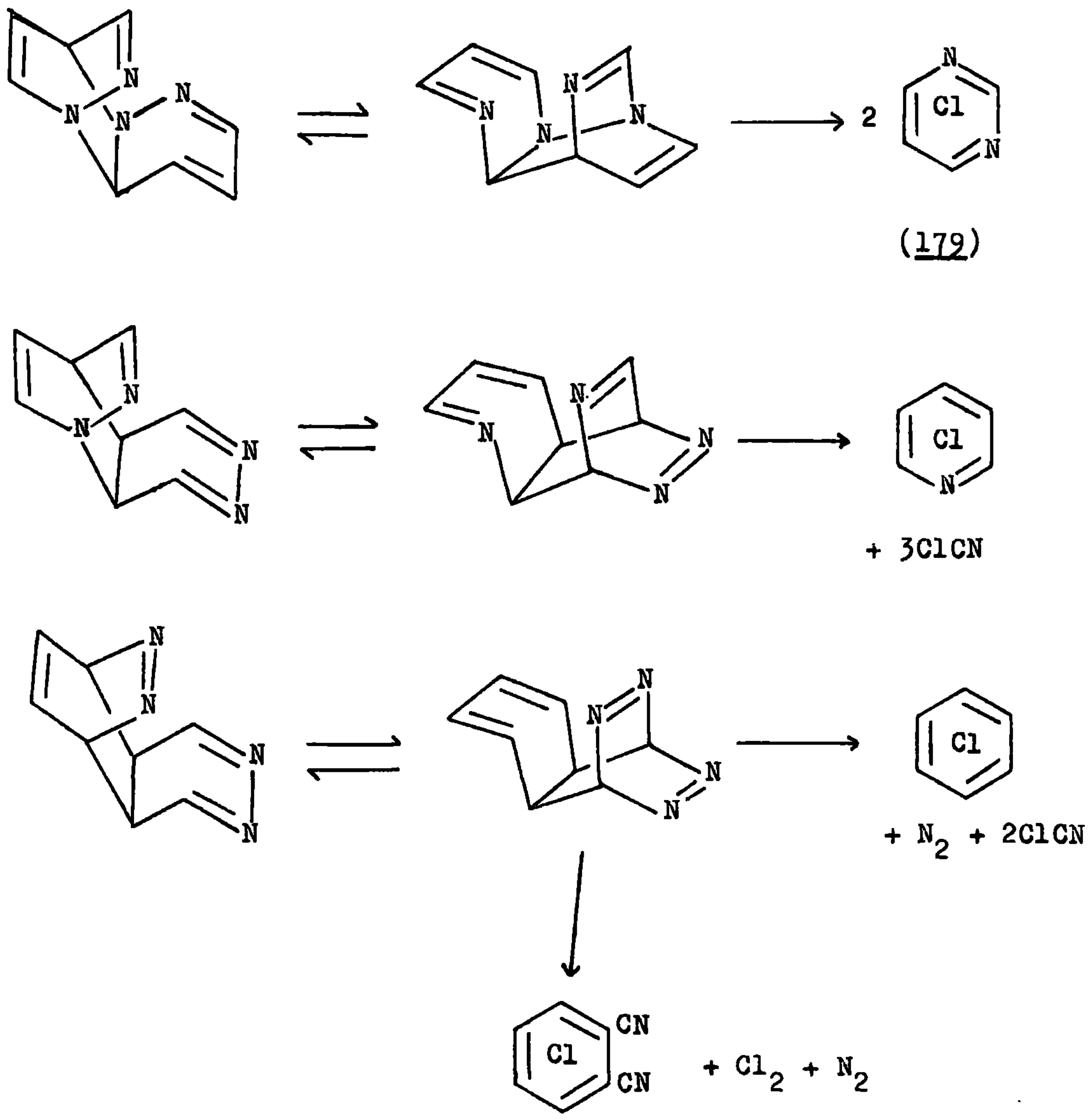
3. A Possible Bimolecular Mechanism

Recently, the results of the pyrolysis of tetrachloropyridazine (166) at 350°C in a sealed tube has suggested a possible bimolecular mechanism.[142] The same products were observed as were previously observed in these laboratories in a flow system,[139] with, in addition, a 6% yield of tetrachloropyrimidine (179). The reaction was found to be pressure dependent, with (166) having a half-life of 4 days at 1 atmosphere and 20 days at 0.1 atmospheres. The formation of Diels-Alder dimers of (166) was proposed to account for rearranged and disproportionated products and nitrogen extrusion from the dimer to give some of the more complex products. (Scheme IX.6).

The above results cast doubts on the molecularity of thermal rearrangements of perfluoroalkylpyridazines in static systems. The rearrangements occurring in flow and vacuum systems are much less likely to involve bimolecular processes. The authors also cast doubts unjustifiably on the photochemical rearrangements, for which the unimolecularity has been established by the isolation of the intermediate para-bonded species.

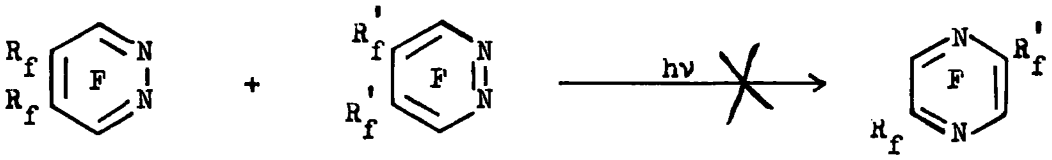
The aim of the work described in the following sections was to prove

Scheme IX.6 All unmarked positions carry chlorine.



the unimolecular nature of both the photochemical and thermal rearrangements of perfluoroalkylpyridazines, by demonstrating the absence of any cross-over products when different pyridazines are rearranged in a mixture.

i.e.



IX.B PHOTOLYSIS OF PERFLUOROALKYLPYRIDAZINES

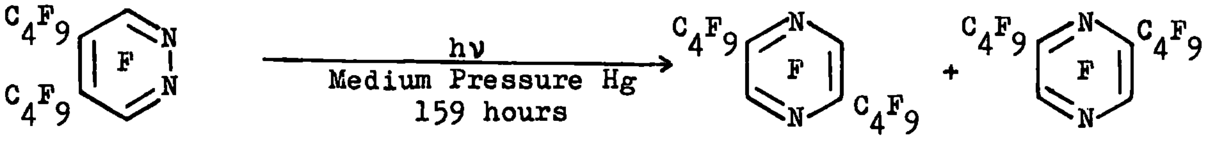
The irradiations were performed in sealed silica tubes, using medium pressure mercury lamps. Under these conditions the para-bonded intermediates have not been isolated. Before performing the photolysis of mixtures the photolyis of the individual pyridazine derivatives was repeated.

The pyridazine derivatives used were prepared as described in Section D.

1. Individual Pyridazine Derivatives

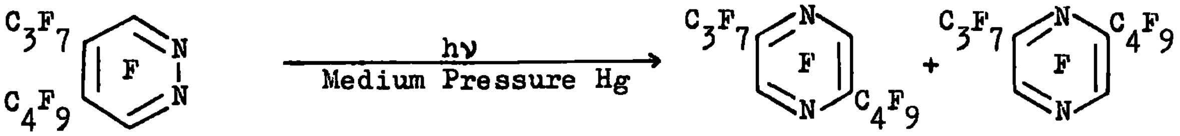
The photolysis of perfluoro-4,5-di-isopropylpyridazine (138), -4-isopropylpyridazine (137), and -4-s-butylpyridazine (141) in the vapour phase, gave the corresponding pyrazine derivatives (147), (146) and (150), as reported previously.[134] There was no evidence of any exchange of substituent groups. For example, cross-over of C_3F_7 during the rearrangement of the 4-isopropylpyridazine (137) would give tetrafluoropyrazine and di-isopropylpyrazine (147).

In contrast to the earlier report, perfluoro-4,5-di-s-butylpyridazine (142) gave a product mixture containing some perfluoro-2,6-di-s-butylpyrazine (153). The new pyridazine derivative, perfluoro-4-isopropyl-5-s-butylpyridazine (180) also gave a mixture of the 2,5- and 2,6-pyrazines (181) and (182), which were separated by preparative g.l.c. and their structures assigned by comparison of the ^{19}F n.m.r. shifts of the ring fluorines with those in the di-s-butyl compounds (151) and (153).



(142) (151) (153)

68% 14%

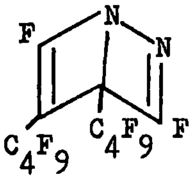


(180) (181) (182)

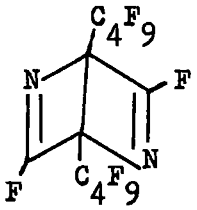
75% 9%

There was no evidence of any exchange of substituent groups in this reaction, to give di-isopropyl- and di-s-butyl- products.

These rearrangements to the 2,6-diperfluoroalkylpyrazines were worthy of further investigation, as they introduce a further factor which cannot be accomodated by the mechanism involving para-bonded intermediates. When the irradiation of perfluoro-4,5-di-s-butylpyridazine (142) at 300nm under transference was repeated, however, the para-bonded species (142a) and (142b) were obtained and these both gave only the 2,5-pyrazine (151) on thermal rearomatisation. Thus, the route to (151) is confirmed but the origin of the 2,6-isomer (153),formed by photolysis in a sealed silica tube on irradiation with medium pressure mercury lamps, is unknown.



(142a)



(142b)

When (142) was irradiated in a sealed tube, with the liquid phase shielded, (153) was still formed, demonstrating that this rearrangement is not occurring in the liquid phase. It was also possible that (153) was formed by rearrangement of the 2,5-pyrazine (151) but (151) was recovered unchanged after photolysis for 93 hours, under the same conditions. This did not rule out the possibility that the conversion of (151) to (153) might require sensitisation by the presence of a pyridazine derivative.

A mixture of (151) and perfluoro-4,5-di-isopropylpyridazine (138) was, therefore, irradiated for 72 hours and (151) was unchanged, thus, ruling out this possibility, unless it is specifically perfluoro-4,5-di-s-butylpyridazine which sensitises the reaction.

It appears that (153) is formed from the original pyridazine (142). A possible explanation for the formation of (153) is a route involving diazabenzvalene intermediates, like that proposed for thermal rearrangements. (Scheme IX.5, p.121; $R_1 = R_2 = C_4F_9$). The thermal processes give mainly pyrimidines as products, however, whereas no pyrimidine derivative was detected from the photolysis experiments. Nevertheless, there is no obvious alternative explanation at the moment of writing.

Compound (142) was also irradiated for an extended period (212 hours) under identical conditions. This gave a high-boiling orange oil, the major components of which were shown by g.l.c. with mass spectroscopy to result from loss of CF_2 or C_2F_4 fragments. In view of the decreased volatility compared to (142), these probably have cyclic structures. A similar mixture was obtained by prolonged photolysis of the pyrazine (151).

2. Pyridazine Mixtures

Mixtures of perfluoro-4,5-di-isopropylpyridazine (138) and perfluoro-4,5-di-s-butylpyridazine (142); and perfluoro-4-isopropylpyridazine (137) and perfluoro-4-s-butylpyridazine (141); were irradiated under the above conditions. In both cases the products were the same as when the individual pyridazine derivatives were irradiated separately and there was no cross-over of substituent groups.

3. Conclusion

The results support the unimolecular mechanism for the rearrangement of perfluoro-4,5-di-alkylpyridazines to -2,5-di-alkylpyrazines, via intermediate para-bonded species, as in no case was there any exchange of substituent groups, indicative of a bimolecular process. The route to the 2,6-dialkylpyrazines (153) and (182) is undetermined.

An attempt to triplet sensitize the rearrangement of perfluoro-4,5-di-isopropylpyridazine (138) by irradiation at 253.7nm, in solution with benzophenone (E_T = 69 kcal/mole) was unsuccessful. This means that either triplet states are not involved in the rearrangement or a sensitizer of higher triplet energy is required.

IX.C PYROLYSIS OF PERFLUOROALKYLPYRIDAZINES

The greatest possibility of the involvement of bimolecular processes in the thermal rearrangement of pyridazine derivatives is during pyrolysis in static systems. Previously, only perfluoro-4,5-di-isopropylpyridazine (138) had been efficiently isomerised under static conditions; pyrolysis in a sealed nickel tube at 370°C giving almost 100% conversion to perfluoro-4,5-di-isopropylpyrimidine (172) after 16 hours.[141]

The pyrolyses described in this section were performed in sealed nickel tubes, previously flushed with dry nitrogen. The reaction time was 16 hours in all cases, to enable direct comparison of the conversions obtained. The volatile products were removed from the tubes by transference under vacuum into a cold trap. The amount of recovered material depended, not only on the efficiency of the reaction, but also on how well the tube was sealed in each case, for which there was no test other than performing the reaction.

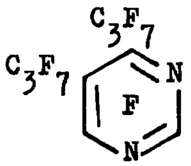
1. Individual Pyridazine Derivatives

(a) Perfluoro-4,5-di-isopropylpyridazine (138)

(i) Effect of Temperature

The effect of varying the temperature on the rearrangement of perfluoro-4,5-di-isopropylpyridazine (138) is shown in Table IX.1.

Table IX.1 Effect of temperature on the rearrangement of perfluoro-4,5-di-isopropylpyridazine (138).

			Product Mixture		
Initial Wt. (138)	Temp.	Recovered Material	(138)	 (172)	Defluorinated Compounds
1.05g	380°C	75%	trace	77%	23%
1.35g	350°C	88%	46%	49%	5%
1.25g	300°C	90%	92%	8%	—

The greatest conversion was obtained at 380°C but at this temperature the recovery was relatively low and a large amount of two defluorinated compounds was formed. These were not mentioned in the previous report[141] and their formation will depend on the state of the nickel tube used. The lower efficiency of these reactions may be due to the small amounts of (138) used. In the previous work a 10g sample was used in a tube the same size (ca. 100ml) and consequently the ratio of the surface area of the walls of the nickel tube to the amount of (138) was much smaller.

No attempt was made to identify the defluorinated compounds but perfluoro-4,5-di-isopropylpyrimidine (172) was separated by preparative g.l.c. and identified by comparison with an authentic sample.[141]

(ii) Effect of Pressure

It was not possible to alter the pressure inside the nickel tubes, other than by changing the quantity of material in them. In Table IX.2 the pressure due to (138) is calculated assuming it to behave as an ideal gas, which it obviously will not. It is reasonable to assume that all of the (138) present is in the vapour phase, however, as compounds such as aniline, iodobenzene, and phenol, which have similar boiling-points to (138) at atmospheric pressure, have saturated vapour pressures of 10-20

Table IX.2 Effect of pressure on the rearrangement of (138) at 350°C.

Initial Wt. (138)	Estimated Pressure Due to (138)	Estimated Total Pressure	Product Mixture		
			(138)	(172)	Defluorinated Compounds
1.11g	1.3 atmos.	3.6 atmos.	24%	64%	12%
4.16g	4.7 atmos.	7.0 atmos.	35%	53%	12%

atmospheres at the temperature of 350°C used for the pyrolyses.[143] At this temperature the pressure due to nitrogen in the tube should be 2.3 atmospheres. The pyrolyses were performed in the same nickel tube immediately after each other, to minimise any variations in the state of the tube and the oven temperature. The recovery of material was almost identical in the two runs, being 88% in the first and 92% in the second.

It can be seen from Table IX.1 that approximately doubling the pressure in the tube has decreased the proportion of (172) in the product mixture. i.e. The half-life of (138) has slightly increased. This is the opposite effect to that expected for a bimolecular process and appears to rule out any bimolecular mechanism for the rearrangement of (138).

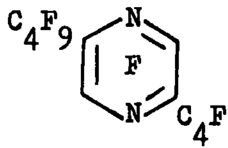
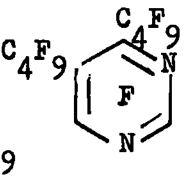
(b) Perfluoro-4,5-di-s-butylpyridazine (142)

The pyrolysis of perfluoro-4,5-di-s-butylpyridazine (142) has not previously been reported. The results obtained in static systems at a variety of temperatures are summarised in Table IX.3. The major product was perfluoro-4,5-di-s-butylpyrimidine (183), which is a new compound, but, in addition, there was a significant yield of perfluoro-2,5-di-s-butylpyrazine (151). Compounds (183) and (151) were purified by preparative g.l.c. and the pyrazine (151) was identified by comparison with the sample previously obtained by photolysis of (142).

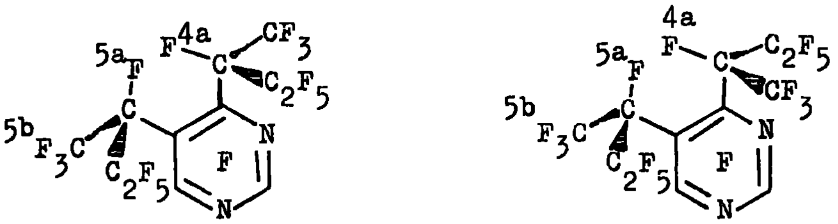
The pyrimidine (183) was identified as the 4,5-isomer by the similarity

Table IX.3

Rearrangement of perfluoro-4,5-di-s-butylpyridazine (142).

			Product Mixture			
Initial Wt. (142)	Temp.	Recovered Material	(142)	 (151)	 (183)	Unknowns
1.73g	380°C	63%	-	18%	67%	15%
1.55g	350°C	75%	-	14%	80%	6%
1.40g	320°C	63%	-	10%	84%	6%
1.12g	300°C	84%	1%	8%	85%	6%
1.40g	260°C	93%	38%	6%	52%	4%

of the ^{19}F n.m.r. shifts of the ring fluorines to those in the perfluoro-di-isopropyl compound (172). In structures such as (183) it is known that the perfluoroalkyl groups adjacent to ring nitrogen adopt the average conformation shown below, with alkyl groups flanking the nitrogen and giving sharp ^{19}F n.m.r. signals.[144,145,133] In the perfluoro-4,5-di-isopropyl pyrimidine (172) the conformation is effectively fixed and a large through-space coupling of 180 Hz is observed between the adjacent tertiary fluorine atoms of the perfluoroisopropyl groups.[141] No such coupling is observed in the spectrum of (183), due to the accidental equivalence of the tertiary fluorine atoms 4a and 5a. The presence of two non-equivalent structures is shown by the 5b CF_3 group giving two signals at 73.8 and 75.3ppm, integrating as 1½ fluorines each. This is not due to coupling, as the separation in Hz alters on changing to an n.m.r. spectrometer operating



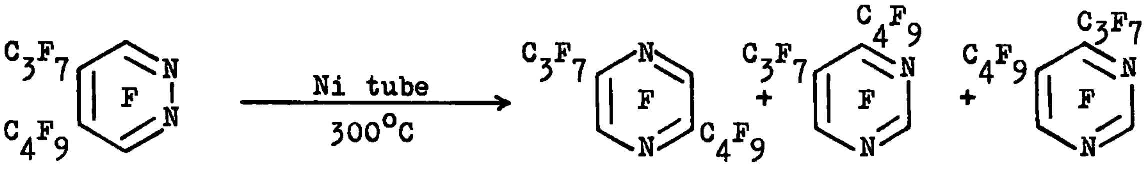
'cis' (183) 'trans'

at a different field strength. It can be explained by the presence of two isomers, which are effectively cis- and trans- isomers because of the locked conformation. On heating to 140°C, increased rotation must decrease the difference between them as the two signals due to 5b merge to give a broad resonance at 74.3ppm. (For the complete spectrum see Appendix 1).

It is evident from the data in Table IX.3 that the rearrangement of (142) occurs much more readily than that of the di-isopropyl compound (138), virtually 100% conversion being obtained at 300°C. A large amount of rearrangement was even observed at a temperature as low as 260°C.

The formation of the 2,5-pyrazine (151) rather than the 2,6-isomer agrees with the proposed diazabenzvalene mechanism. (Scheme IX.5, p.121). It was suggested that the formation of a 2,5-pyrazine (147) from perfluoro-4,5-di-isopropylpyridazine (138) and a 2,6-pyrazine (178) from the di-ethyl compound (140) was due to a greater driving force to separate the perfluoroalkyl groups in the diazabenzvalene intermediates as the size of the groups was increased. In (142) the size of the groups is even greater and, not only is the 2,5-pyrazine (151) formed, but it is formed under conditions where the di-isopropyl compound (138) gives no pyrazine derivative.

(c) Perfluoro-4-isopropyl-5-s-butylpyridazine (180)



(180) (181) (184) (185)

3% 44% 43%

+ Unknowns 6%

+ (180) 4%

Recovered Material: 83%

The pyridazine (180) was only pyrolysed on one occassion, at 300°C and the recovered material contained only 4% of unreacted (180). There was only a small yield of a pyrazine, identified by g.l.c. with mass spectroscopy, and this had a g.l.c. retention time identical with the 2,5-isomer (181). As would be expected from the diazabenzvalene mechanism, two pyrimidine derivatives (184) and (185) were produced, in approximately equal yield and these were purified by preparative g.l.c. At first sight, the assignment of structures to these compounds might seem to be a difficult task. It was made easy, however, by the fact that the perfluoroalkyl group adjacent to the ring nitrogen gives sharp ^{19}F n.m.r. signals, as described on p.131. Thus, the perfluoroisopropyl group in (185) gives a sharp singlet, whereas in (184) the two CF_3 groups are non-equivalent. Similarly the s-butyl group of (185) shows complex coupling but the only coupling in the s-butyl group of (184) is geminal coupling of the $-CF_2-$ (J = 300 Hz). In (184) through-space coupling can be seen between the adjacent tertiary fluorine atoms (J = 200 Hz) as in the di-isopropyl compound (172). In (185), however, these fluorine atoms are accidentally equivalent, as in the di-s-butyl compound (183).

(d) Perfluoro-4-isopropylpyridazine (137)

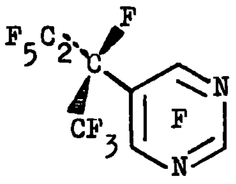
The pyrolysis of perfluoro-4-isopropylpyridazine (137) had previously been performed only in a flow system[141] and gave an inseparable mixture of perfluoro-4-isopropylpyrimidine (175) and perfluoro-5-isopropylpyrimidine (174), as expected on the basis of the diazabenzvalene mechanism. The 4-isopropyl compound (175) is known but (174) was only identified from the n.m.r. spectrum of the mixture.

When (137) was pyrolysed in a nickel tube at 400°C for 16 hours, the recovered material (81%) contained only 16% of the pyrimidines, together with (137) and some minor defluorinated compounds. The pyrimidines were separated from other material by preparative g.l.c. and shown by n.m.r. to be a mixture of (174) and (175) in the ratio of approximately 4 : 3.

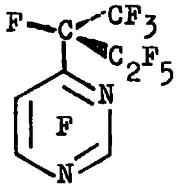
(e) Perfluoro-4-s-butylpyridazine (141)

The pyrolysis of perfluoro-4-s-butylpyridazine (141) has not previously been reported. On pyrolysis in a nickel tube at 350°C for 16 hours, there was a recovery of 77% and this material contained only 32% of a mixture of pyrimidine derivatives. At 400°C the recovery decreased to 72% but this consisted of 94% pyrimidines and a defluorinated impurity, with no unreacted (141). Increasing the size of the perfluoroalkyl group has, therefore, increased the ease of rearrangement compared to the 4-isopropyl compound (137).

The pyrimidines were separated from other material by preparative g.l.c. and shown by n.m.r. to be an approximately 1 : 1 mixture of perfluoro-5-s-butylpyrimidine (186) and the known compound perfluoro-4-s-butylpyrimidine (187).[146] The ^{19}F n.m.r. spectrum of (186) is interesting in that the 4- and 6- fluorine atoms are non-equivalent, demonstrating that there is restricted rotation of the perfluoro-s-butyl group at room temperature, a phenomenon that has been observed in other systems.[146]



(186)



(187)

(f) Conclusion

The results are all in agreement with the proposed diazabenzvalene mechanism and the effect of pressure on the rearrangement of perfluoro-4,5-di-isopropylpyridazine (138) appears to rule out the possibility of a bimolecular mechanism.

An increase in size of the perfluoroalkyl substituents from C_3F_7 to C_4F_9 is found to make the rearrangement remarkably easier. It is unlikely that this can be attributed to an increase in steric crowding raising the energy of the initial state, as the products are equally crowded and it may be due to increased stabilisation of the intermediates.

2. Mixtures

Mixtures were pyrolysed in nickel tubes for 16 hours and the products analysed by g.l.c. with mass spectroscopy. In no case was any cross-over of substituent groups observed but, instead, an unusual catalysis of the rearrangement of the less readily rearranged pyridazine by the more easily rearranged derivative.

(a) Perfluoro-4,5-di-isopropylpyridazine (138) and Perfluoro-4,5-di-s-butylpyridazine (142)

A 1 : 1 mixture of pyridazines (138) and (142) was first pyrolysed at 350°C, a temperature at which both rearrange to a significant extent, as it was felt that an exchange process would be more likely under these conditions. The recovered di-isopropyl- compound was completely rearranged to the pyrimidine form, compared to conversions of 49 - 64% when it was pyrolysed alone at this temperature. (See pp.129,130).

This experiment was repeated at 300°C, at which temperature (138) was only 8% rearranged on its own. In the mixture 91% of the recovered di-isopropyl compounds were in the pyrimidine form. It is clear that something in the mixture has a remarkable catalytic effect on the rearrangement of (138).

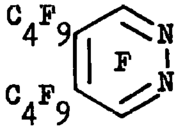
(b) Catalysis of Other Pyridazines by Perfluoro-4,5-di-s-butylpyridazine

To see if other rearrangements could be catalysed by the presence of perfluoro-4,5-di-s-butylpyridazine (142), mixtures with tetrafluoropyridazine (136) and 4,5-dichlorodifluoropyridazine (167) were pyrolysed at 300°C. Both of these compounds were unchanged when pyrolysed separately at this temperature.

(i) Tetrafluoropyridazine (136)

The rearrangement of tetrafluoropyridazine (136) at 300°C was also catalysed by perfluoro-4,5-di-s-butylpyridazine (142). After pyrolysis of a 1 : 1 mixture of (136) and (142), 33% of the recovered tetrafluoro-compounds were present as tetrafluoropyrimidine (171). A number of different molar ratios of (136) and (142) were pyrolysed to see if there was a constant relationship between the number of moles of each rearranged. The results are summarized in Table IX.4.

Table IX.4

Molar Ratio				
 (136)	:	 (142)	No. moles (136) isomerised / No. moles (142) isomerised	No. moles (136) isomerised / No. moles (142) Initially present
1	:	1	0.31	0.26
4	:	1	1.29	1.06
10	:	1	2.73	1.44

The results show that there is clearly no constant relationship between the number of moles of (136) and (142) rearranged. Also, when (136) is in excess, each molecule of (142) can catalyse the rearrangement of more than one molecule of (136). This rules out the formation of an intermediate 1 : 1 complex or Diels-Alder adduct between (136) and (142) as an explanation for the catalytic effect. This is discussed more fully in sub-section (e).

It was interesting that in the 10 : 1 mixture 13% of the recovered di-butyl compounds were still present as the pyridazine (142). Thus, we are also seeing the reverse of the catalytic effect, i.e. inhibition of the rearrangement of the more easily rearranged molecule.

A 1 : 1 mixture of (136) and (142) was also pyrolysed at 300°C in a pyrex tube, sealed at atmospheric pressure. Again rearrangement of (136) occurred, demonstrating that the catalysis is not dependent on the use of a nickel tube. It would be difficult to find out if it will occur under flow or vacuum conditions, however, because of the large difference in volatility between the two compounds.

The combined product mixtures were separated by preparative g.l.c. and the identity of the rearrangement product from (136) confirmed as tetrafluoropyrimidine (171).

(ii) 4,5-Dichlorodifluoropyridazine (167)

A 2 : 1 mixture of (167) and perfluoro-4,5-di-s-butylpyridazine (142) was pyrolysed at 300°C. In the product, 68% of the di-s-butyl compounds were still in the pyridazine form, i.e. there had been a large inhibiting effect by the dichloro-compound (167). The dichloro compound was 14% rearranged to a compound of the same mass but a different mass spectral break-down pattern, which was consistent with a pyrimidine. This was assumed to be 4,5-dichlorodifluoropyrimidine but it was not isolated. Thus (142) appears to have catalysed the rearrangement of (167), while its own rearrangement has been inhibited.

(c) Further Investigation of the Catalysis of the Rearrangement of Tetrafluoropyridazine (136)

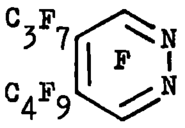
To clarify the nature of the catalysis of the rearrangement of tetrafluoropyridazine (136) by perfluoro-4,5-di-s-butylpyridazine (142), certain possibilities had to be ruled out. Firstly, the rearrangement may have been taking place in the liquid phase, with the less volatile (142) acting as a solvent. When (136) was pyrolysed at 300°C with the inert fluorocarbon perfluoro-1-methyldecalin as the solvent, however, no rearrangement was observed.

Secondly, the catalysis had been observed at a temperature at which (142) itself rearranges and so one of the products from (142) may have been the catalyst. Mixtures of (136) with the major products from (142), perfluoro-4,5-di-s-butylpyrimidine (183) and perfluoro-2,5-di-s-butylpyrazine (151), were unchanged after pyrolysis at 300°C, however, which rules out this possibility, unless one of the minor products is involved. A mixture with perfluoro-2,5-di-isopropylpyrazine (147) was also unchanged under these conditions.

The evidence points towards the catalyst being either the pyridazine derivative (142) itself, or an intermediate in its rearrangement. The next question was whether other pyridazine derivatives could also behave as catalysts. A 7 : 1 mixture of (136) with perfluoro-4-isopropyl-5-s-butylpyridazine (180) was pyrolysed at 300°C and the recovered tetrafluoro-compounds contained 18% tetrafluoropyrimidine (171). As well as the rearrangement of (136) being catalysed, that of (180) was significantly inhibited, 24% being unchanged. The results again showed no 1 : 1 relationship between the amounts of the two pyridazines rearranged. (See Table IX.5).

Table IX.5

Molar Ratio

 (136)	:	 (180)	$\frac{\text{No. moles (136) isomerised}}{\text{No. moles (180) isomerised}}$	$\frac{\text{No. moles (136) isomerised}}{\text{No. moles (180) Initially present}}$
7	:	1	1.45	1.15

A 4 : 1 mixture of (136) with perfluoro-4,5-di-isopropylpyridazine (138) was pyrolysed at 300°C, at which temperature there is only a small conversion of (138) on its own, and no rearrangement of (136) was observed. In fact, only a trace of (138) rearranged to perfluoro-4,5-di-isopropylpyrimidine (172). This suggests that the catalytic effect is only observed at a temperature at which the catalysing pyridazine derivative is itself readily rearranged. Even at 350°C, no catalysis was observed on pyrolysing a 10 : 1 mixture of (136) and (138) but the rearrangement of (138) was greatly inhibited.

It was thought that the inhibition of the rearrangement of the more reactive pyridazine derivative might simply be a dilution effect. That this was not so was demonstrated when a 1 : 10 mixture of perfluoro-4,5-di-isopropylpyridazine (138) and the inert fluorocarbon perfluoro-1-methyldecalin was pyrolysed at 350°C and no inhibition was observed. In fact, there was a slight increase in the conversion of (138). When (138) was pyrolysed in a 1 : 10 mixture with hexafluorobenzene, however, an inhibiting effect was observed of similar magnitude to that of tetrafluoropyridazine (136). It would appear that to inhibit the rearrangement of (138) requires the presence of an aromatic system of some kind.

(d) Catalysis by Perfluoro-4-s-butylpyridazine (141)

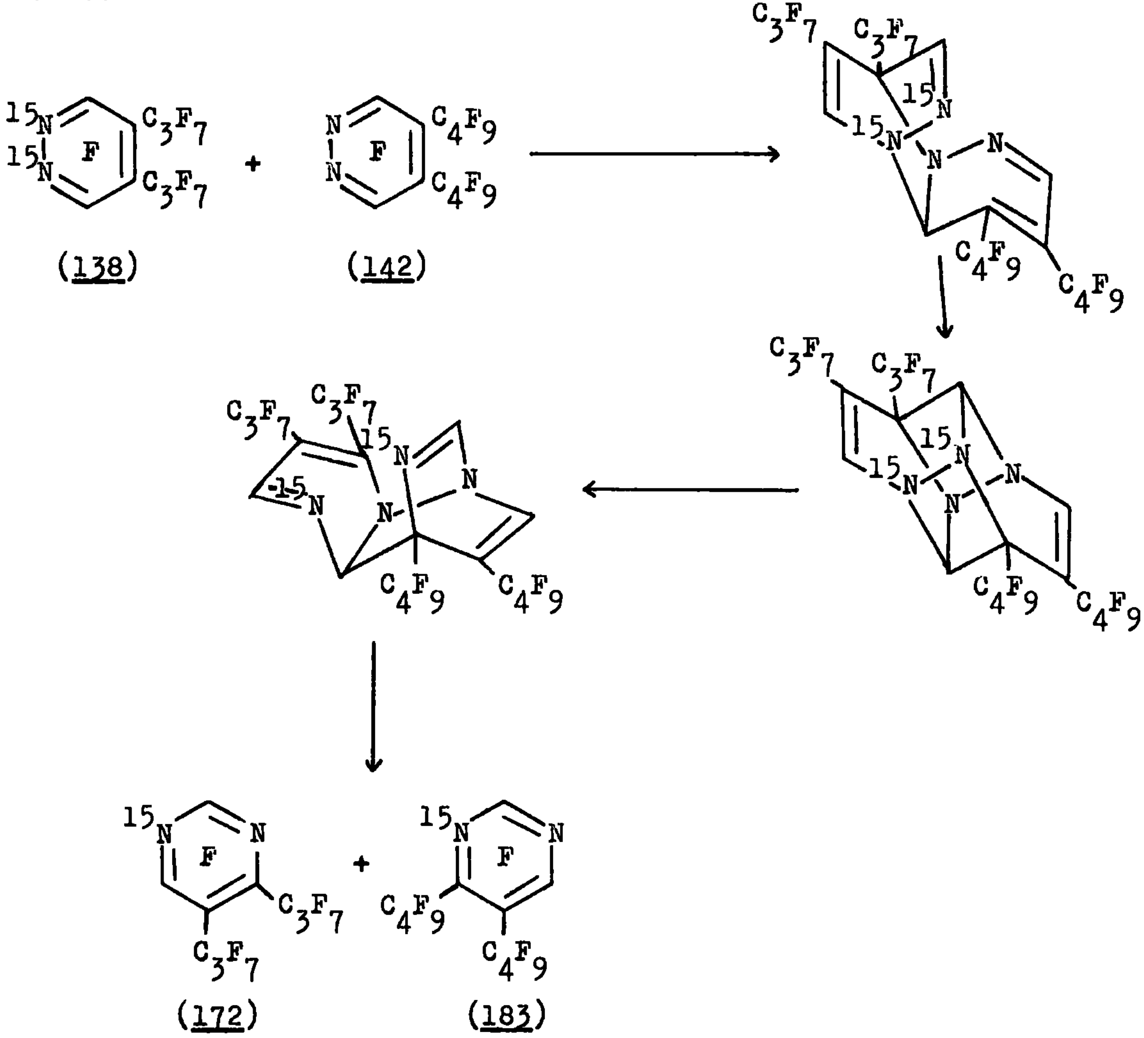
Perfluoro-4-s-butylpyridazine (141) is completely rearranged on pyrolysis at 400°C, compared to a conversion of only 16% for perfluoro-4-isopropylpyridazine (137) at the same temperature. On pyrolysis of a 4 : 1 mixture of (137) and (141) under identical conditions, however, the conversion of both was approximately 35%. Thus, the rearrangement of (137) was catalysed and that of (141) inhibited. The ratio of the number of moles of (137) rearranged to the number of moles of (141) rearranged was 2.70, again ruling out any 1 : 1 relationship.

(e) Mechanism of the Catalysis

Three possible mechanisms were originally considered. These were :

(i) Formation of a Diels-Alder intermediate, as in Scheme IX.6, p.124. By this mechanism, only one molecule of the less readily rearranged pyridazine derivative could be rearranged per molecule of catalyst and so it is clearly ruled out by the experimental results. Nevertheless, one more experiment was performed to further demonstrate its non-applicability. As can be seen from Scheme IX.7, this mechanism would not involve exchange of substituent groups but it would involve exchange of ring nitrogen.

Scheme IX.7



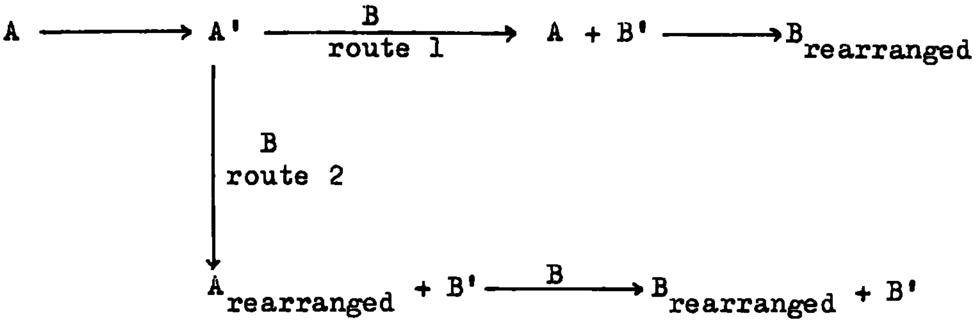
All unmarked positions carry fluorine.

A small amount of doubly ^{15}N-labelled perfluoro-4,5-di-isopropylpyridazine (138) was prepared, in a 50/50 mixture with the unlabelled compound. This showed two mass spectral parent peaks at 452 and 454, of approximately equal size. It was pyrolysed at 300°C with a large excess (5 : 1) of unlabelled perfluoro-4,5-di-s-butylpyridazine (142). By the bimolecular process in Scheme IX.7, virtually all of the dilute doubly labelled (138) should react with unlabelled (142) to give a singly labelled product. Thus, in the perfluoro-4,5-di-isopropylpyrimidine (172) produced, the parent peak at 454 should have disappeared and been replaced by a large peak at 453. On analysis of the mixture by g.l.c. with mass spectroscopy, (172) was found to have parent peaks at 452 and 454, of approximately equal size. Although the Micromass instrument did not allow accurate calibration of the peak sizes, it is clear that the Diels-Alder mechanism cannot occur to any significant extent.

This result not only rules out the Diels-Alder mechanism as an explanation for the catalytic process but also for the thermal rearrangement of the individual perfluoroalkylpyridazines. This leaves the diazabenzvalene mechanism (Scheme IX.5, p.121) as the only mechanism that has been suggested that can adequately account for the products observed.

(ii) Formation of a loose complex [A----B], where A is the catalysing molecule and B is the pyridazine derivative being catalysed. In this complex the activation energy for rearrangement of B must be decreased and also that of A must be increased to account for the inhibition observed. This mechanism also requires a 1 : 1 relationship between the number of molecules of A and B rearranged, unless the complex breaks down to give unchanged A and rearranged B. Although there is no obvious reason why the latter possibility should occur, if it is postulated the dividing line between this mechanism and route 1 in the third mechanism overleaf becomes very fine.

Scheme IX.8



(iii) The third and favoured mechanism is shown in Scheme IX.8. By this mechanism, A becomes activated by collision in the normal way, to give the intermediate A'. A' may just be a highly vibrationally excited state, or alternatively it may be the postulated diazabenzvalene intermediate. In either case it must be able to transfer more energy on collision than any molecule of B normally does at this temperature. On collision with B, it gives up this excess energy to produce B', which ultimately leads to rearranged B. During this transfer of energy, A' may fall back to its original state, in which case it can become activated again and repeat the process (route 1). It is probably more likely, however, that A' goes on to give rearranged A on losing its excess energy (route 2), in which case a molecule of A is lost from the reaction mixture. However, B' can behave similarly and carry on the catalytic process. Thus, more than one molecule of B can be rearranged for each molecule of A.

This type of process can also explain the inhibition of the rearrangement of the more readily rearranged molecule A. If A' can normally activate another molecule of A in the process of producing rearranged A, by a route analogous to route 2 above, then we have in effect a chain process. This can be interrupted if the energy is transferred instead to a less reactive molecule B, which does not obtain enough energy to rearrange itself.
It is interesting that hexafluorobenzene has an inhibiting effect but perfluoro-1-methyldecalin does not. This suggests that the transferred

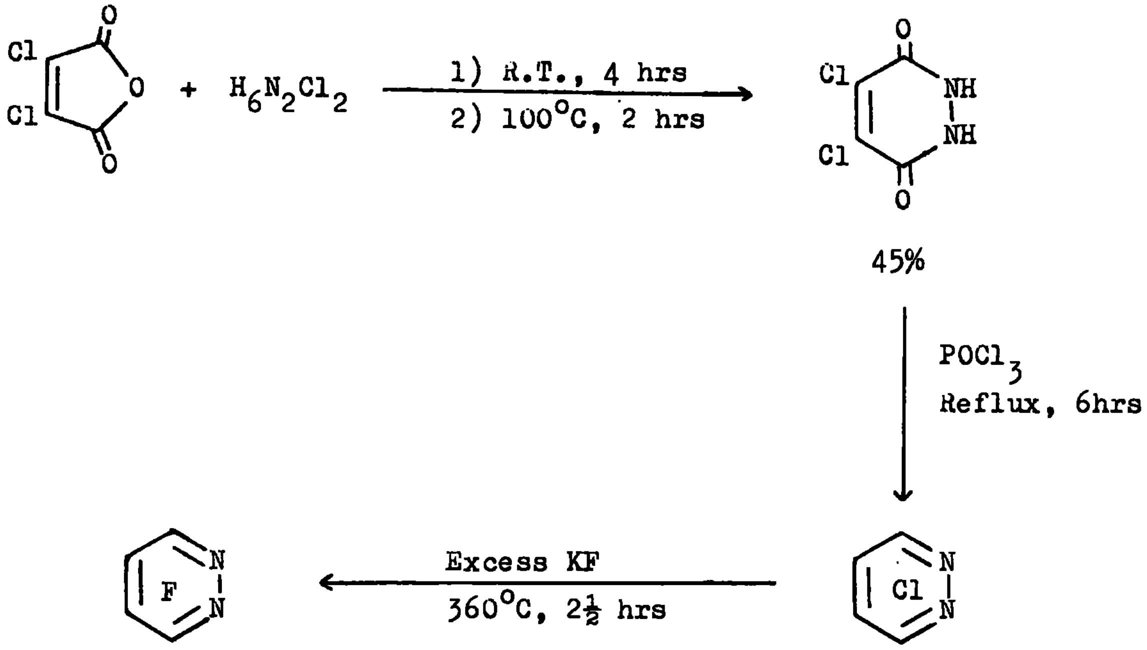
energy is associated specifically with an aromatic ring. Possibly it goes into vibrational modes associated with the out of plane distortions of the ring which are necessary to produce this type of rearrangement.

A variation on this mechanism was also considered, where A' is an excited triplet state produced thermally. In this case the energy transfer process is the well-known triplet sensitization reaction. However, this seems unlikely, as it has not been possible to produce a triplet sensitized rearrangement of a perfluoroalkylpyridazine by irradiation in the presence of benzophenone as a sensitizer.

IX.D PREPARATION OF PYRIDAZINE DERIVATIVES

1. Tetrafluoropyridazine (136)

Tetrafluorpyridazine (136) was prepared by technical staff, by the route below. This differs slightly from the published method,[147] in that dichloromaleic anhydride is used instead of maleic anhydride, eliminating an autogenous reaction with phosphorus pentachloride.

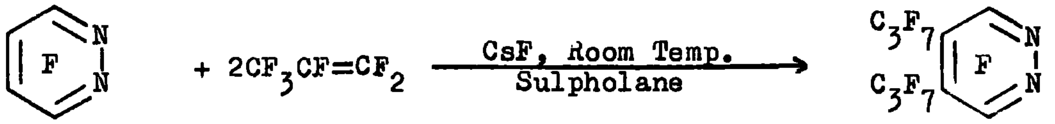


(136) (166)

2. Perfluoroalkylpyridazines

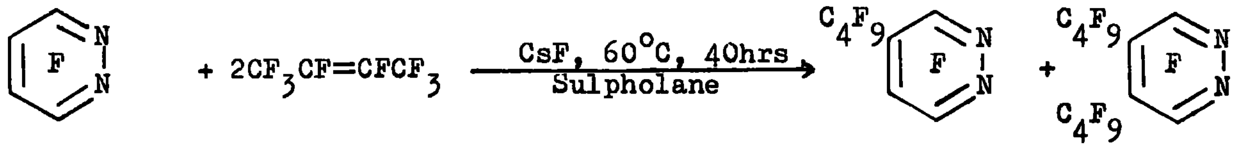
The perfluoroalkylpyridazines were prepared by the well known polyfluoroalkylation reaction.[76] This involves addition of fluoride ion to a perfluoro-olefin in an aprotic solvent, to form the corresponding carbanion, which then attacks the tetrafluoropyridazine, resulting in nucleophilic displacement of fluoride ion. These reactions occur efficiently at atmospheric pressure, the temperature necessary depending on the reactivity of the carbanion.

Perfluoro-4,5-di-isopropylpyridazine (138) and perfluoro-4,5-di-s-butylpyridazine were prepared by published routes,[148,146] as shown below.



(136) (44) (138)

81%

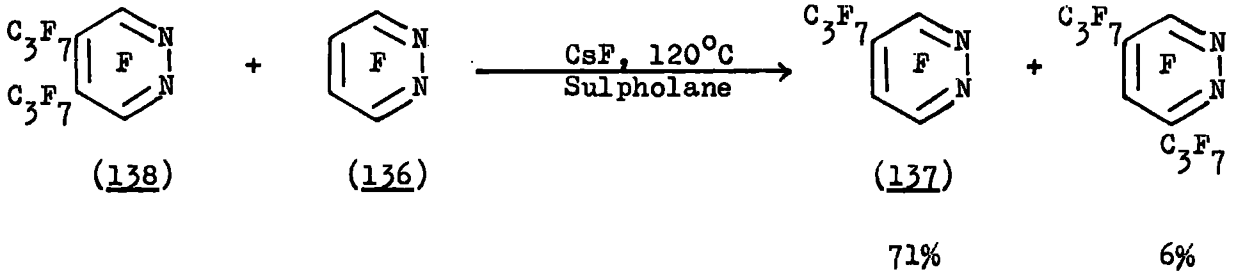


(136) (77) (141) (142)

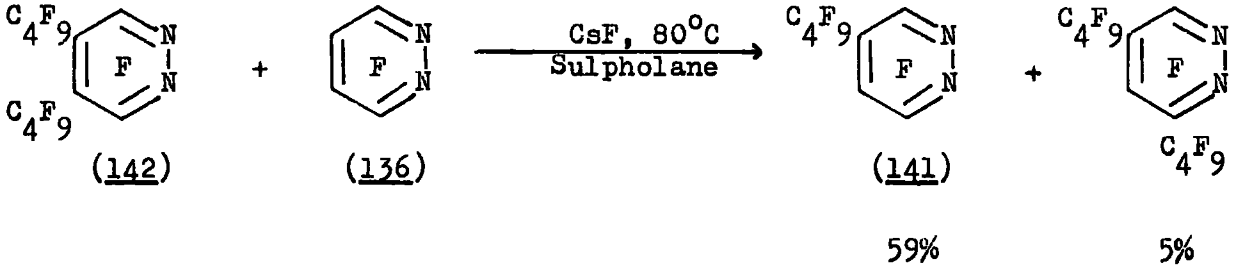
20% 58%

The latter gave a complex product mixture, requiring separation by preparative g.l.c. Other components, which were not obtained pure, were perfluoro-3,5-di-s-butylpyridazine and some defluorinated compounds, which were not mentioned in the previous report. This is another example of defluorination induced by fluoride ion, (for other examples see Chapter IV).

Perfluoro-4-isopropylpyridazine (137) cannot be prepared efficiently by reaction between equimolar amounts of (136) and (44) at room temperature, as the rate of substitution by heptafluoroisopropyl anion is greater for attack on (137) than on (136). This reaction is reversible, however, and at higher temperatures fluoride ion will displace $C_3F_7^-$ from the di-isopropyl compound (138), enabling (137) to be prepared by the method below.[149]



Perfluoro-4-s-butylpyridazine (141) was prepared by a similar method, from the di-s-butyl compound (142) :



The preferable route to perfluoro-4-isopropyl-5-s-butylpyridazine (180) would be by fluoride-ion-induced reaction between perfluoro-4-isopropyl-pyridazine (137) and octafluorobut-2-ene (77), as the preparation of (137) is relatively straightforward, involving no difficult separations. Unfortunately, the temperature required to introduce the s-butyl group into (137) was also sufficient to cause some displacement of the isopropyl group. The result was that the (180) produced contained inseparable traces of the di-isopropyl- and di-s-butyl compounds, (138) and (142). Compound (180) was prepared from perfluoro-4-s-butylpyridazine (141) very easily, however, by fluoride-ion-induced reaction with hexafluoropropene (44) at room temperature but the preparation of (141) is itself a long and tedious process.

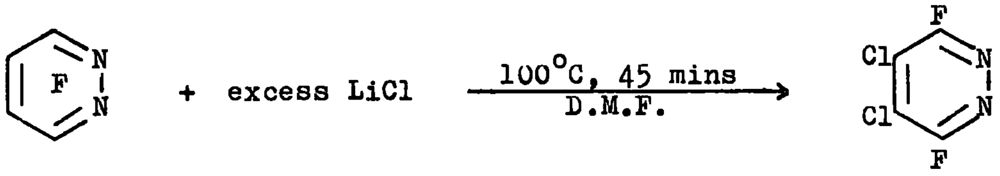
(141) (44) (180)

97%

The ^{19}F n.m.r. spectrum of (180) is interesting as it shows a large through-space coupling of 230 Hz between the two tertiary fluorine atoms of the adjacent perfluoroalkyl groups. This is invariant at up to 160°C, which means that there must be a very high energy barrier to free rotation of the groups. This coupling can not be seen in the perfluoro-di-isopropyl- or -di-s-butyl compounds because the tertiary fluorines are equivalent.

3. 4,5-Dichlorodifluoropyridazine (167)

4,5-Dichlorodifluoropyridazine (167) was prepared in good yield by reacting tetrafluoropyridazine (136) with lithium chloride in D.M.F. at 100°C for about 45 minutes.[150]

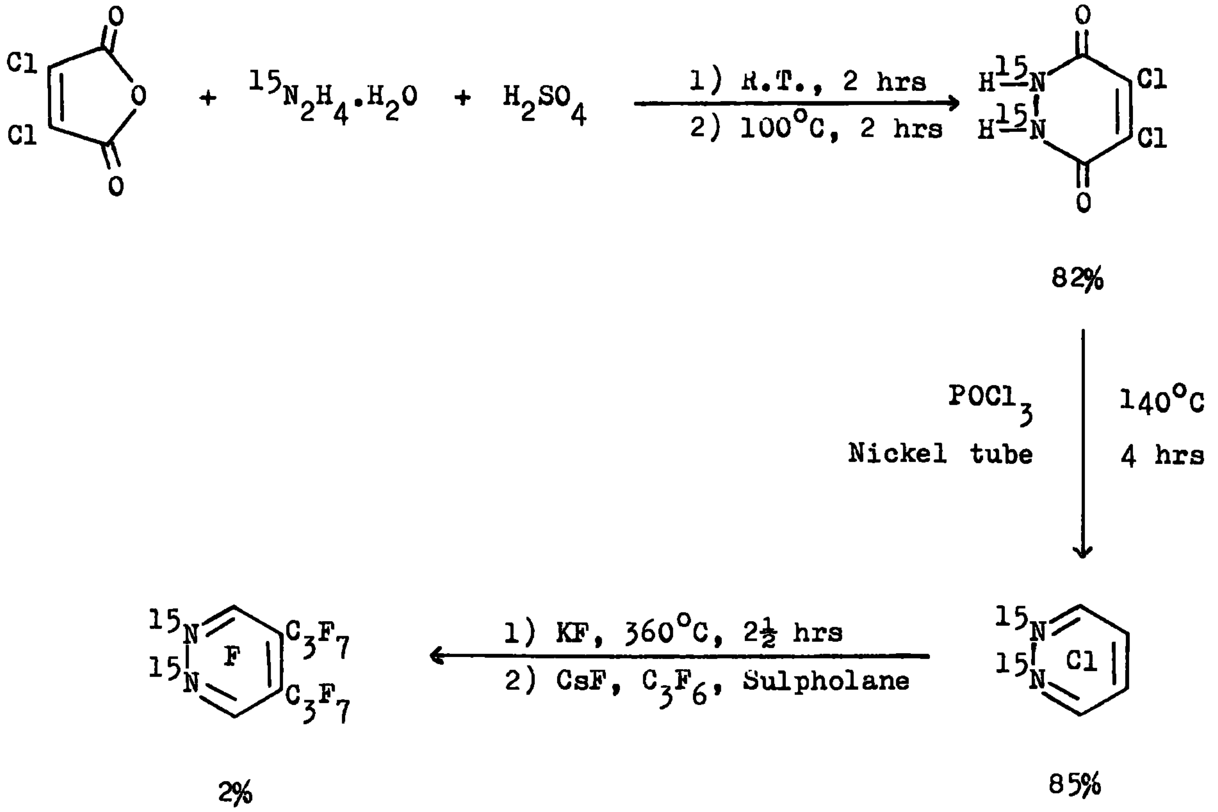


(136) (167)

80%

4. ^{15}N-Labelled Perfluoro-4,5-di-isopropylpyridazine

The route to the labelled derivative is shown overleaf. The starting point was an aqueous solution of 95.4% ^{15}N hydrazine, which was acidified with sulphuric acid before the first stage. The product from the first stage was diluted with an equivalent amount of unlabelled compound before performing the chlorination. It had been discovered using unlabelled compound that the yield from the chlorination was greatly increased by performing the reaction in a sealed nickel tube, at an elevated



temperature, rather than the normal method of refluxing at atmospheric pressure (p.143). The fluorination stage with potassium fluoride was also performed in a nickel tube and this must have leaked, as very little labelled tetrafluoropyridazine was obtained. This was polyfluoroalkylated immediately to give a low overall yield of an approximately 50/50 mixture of doubly ^{15}N-labelled and unlabelled perfluoro-4,5-di-isopropylpyridazine.

EXPERIMENTAL

CHAPTER X

EXPERIMENTAL FOR CHAPTER IX

X.A PHOTOLYSIS EXPERIMENTS

1. Reagents

The pyridazine derivatives were prepared as described in Section C.

2. Experimental Procedure

Most experiments were performed in silica tubes, sealed under high vacuum. Unless otherwise stated, no degassing was performed and the liquid phase was unshielded.

The transference experiment was performed using a large silica vessel connected by a transfer arm to a trap. The pyridazine derivative was placed in the silica vessel, frozen down in liquid air, and the system evacuated to the required pressure. The silica vessel was placed in the irradiation zone, with the trap outside it, frozen in liquid air so that volatile material transferred into it.

3. Ultra-violet Sources

Unless otherwise stated, the irradiations were performed in a Hanovia 'Reading' reactor, employing two Hanovia U.V.S. 500 medium pressure mercury lamps, which emit over a wide range of wavelengths. The temperature in the irradiation zone was ca. 80°C. A Rayonet R.P.R. 208 reactor was also used, employing 8 low pressure mercury lamps, providing 120 watts of 253.7nm light, or 8 'Sunlight phosphor' conversion lamps, providing ca. 85 watts of ultra-violet light with maximum output at 300nm.

4. Irradiations Using Medium Pressure Mercury Lamps

(a) Perfluoro-4,5-di-isopropylpyridazine (138)

Perfluoro-4,5-di-isopropylpyridazine (138) (1.50g, 3.32 m.moles) was sealed in a silica tube (34 x 3.7nm) under high vacuum and irradiated for

96 hours. The volatile product (1.32g) was removed from the tube by transference under vacuum into a cold trap and shown by g.l.c. (col.A, 85°C) to be one component, identified as perfluoro-2,5-di-isopropylpyrazine (147) (88% yield), by comparison of its ^{19}F n.m.r. and i.r. spectra with those of an authentic sample.[151] ^{19}F n.m.r. spectrum No.9; i.r. spectrum No.11.

(b) Perfluoro-4-isopropylpyridazine (137)

Perfluoro-4-isopropylpyridazine (137) (0.51g, 1.69 m.moles) was sealed in a silica tube (31 x 2.9cm) under high vacuum and irradiated for 66 hours. The volatile product (0.45g) was removed from the tube by transference under vacuum into a cold trap and shown by g.l.c. (col. A, 80°C) to be one component, identified as perfluoro-2-isopropylpyrazine (146) (88% yield) by comparison of its ^{19}F n.m.r. and i.r. spectra with those of an authentic sample.[134] ^{19}F n.m.r. spectrum No.10; i.r. spectrum No.12.

(c) Perfluoro-4-s-butylpyridazine (141)

Perfluoro-4-s-butylpyridazine (141) (0.48g, 1.36 m.moles) was sealed in a silica tube (34 x 3.7cm) under high vacuum and irradiated for 66 hours. The volatile product (0.41g) was shown by g.l.c. (col. A, 80°C) to be one component, identified as perfluoro-2-s-butylpyrazine (150) (85% yield) by comparison of its ^{19}F n.m.r. and i.r. spectra with those of the authentic compound.[134] ^{19}F n.m.r. spectrum No.11; i.r. spectrum No.13.

(d) Perfluoro-4,5-di-s-butylpyridazine (142)

Perfluoro-4,5-di-s-butylpyridazine (142) (1.54g, 2.79 m.moles) was sealed in a silica tube (34 x 3.7cm) under high vacuum and irradiated for 159 hours. The volatile product (1.29g) was shown by g.l.c. (col. A, 90°C) to contain 3 components in the ratio 74 : 15 : 11. These were separated by preparative g.l.c. and identified as perfluoro-2,5-di-s-butylpyrazine (151) (68% yield; ^{19}F n.m.r. spectrum No.12; i.r. spectrum No.14); perfluoro-2,6-di-s-butylpyrazine (153) (14% yield; ^{19}F n.m.r. spectrum No.13; i.r.

spectrum No.15); and (142); by comparison of their ^{19}F n.m.r. and i.r. spectra with those of authentic samples.[134]

(e) Perfluoro-4-isopropyl-5-s-butylpyridazine (180)

Perfluoro-4-isopropyl-5-s-butylpyridazine (180) (2.38g, 4.74 m.moles) was sealed in a silica tube (36 x 3.9cm) under high vacuum and irradiated for an unknown period between 100 and 170 hours. (A fuse blew during a weekend). The volatile product (2.11g) was shown by g.l.c. (col. A, 90°C) to contain three components, in the ratio 59 : 7 : 34. These were separated by preparative g.l.c. and identified (in order of retention time) as:

(i) Perfluoro-2-isopropyl-5-s-butylpyrazine (181) (75% yield), b.p. 155°C. (Found: C, 26.6; N, 5.6; F,68.2%; M^+, 502. $C_{11}F_{18}N_2$ requires C, 26.3; N, 5.6 F, 68.1%; M, 502). λ_{max}(cyclohexane) 280nm (ϵ 8,600); n.m.r. spectrum No.14; i.r. spectrum No.16.

(ii) Perfluoro-2-isopropyl-6-s-butylpyrazine (182) (9% yield), b.p. 158°C. (Found: C, 26.0; N, 5.9; F, 67.7%; M^+, 502). λ_{max}(cyclohexane) 273nm (ϵ 6,600); n.m.r. spectrum No.15; i.r. spectrum No.17.

(iii) Unchanged (180).

(f) Perfluoro-4,5-di-s-butylpyridazine (142) with the Liquid Shielded

Perfluoro-4,5-di-s-butylpyridazine (142) (0.70g, 1.26 m.moles) was sealed in a silica tube (31 x 3.3cm) under high vacuum and irradiated for 71 hours, with the small liquid phase shielded with metal foil. The volatile product (0.60g) was shown by g.l.c. (col. A, 90°C) to contain perfluoro-2,5-di-s-butylpyrazine (151) (55% by wt.; 61% yield); perfluoro-2,6-di-s-butylpyrazine (153) (18% by wt.; 20% yield); and (142) (27% by wt.).

(g) Perfluoro-2,5-di-s-butylpyrazine (151)

Perfluoro-2,5-di-s-butylpyrazine (151) (1.31g, 2.73 m.moles) was sealed in a silica tube (36 x 3.9cm) under high vacuum and irradiated for 93 hours. The volatile product (1.03g) was shown by g.l.c. (col. A, 90°C) to be one component, identified from its i.r. spectrum as (151).

(h) Mixture of Perfluoro-4,5-di-isopropylpyridazine (138) and Perfluoro-2,5-di-s-butylpyrazine (151)

The title compounds (138) (1.21g, 2.68 m.moles) and (151) (1.61g, 2.92 m.moles) were sealed in a silica tube (33 x 3.9cm) under high vacuum and irradiated for 72 hours. The volatile product (2.53g) was shown by g.l.c. (col. A, 80°C) to contain perfluoro-2,5-di-isopropylpyrazine (147) (33% by wt.; 76% yield); perfluoro-2,5-di-s-butylpyrazine (151) (63% by wt.; 99% recovery); and perfluoro-4,5-di-isopropylpyridazine (138) (4% by wt.).

(i) Prolonged Photolysis of Perfluoro-4,5-di-s-butylpyridazine (142)

Perfluoro-4,5-di-s-butylpyridazine (142) (2.12g, 3.84 m.moles) was irradiated for 212 hours in a sealed silica tube. The volatile product (0.21g) was shown by g.l.c. and g.l.c. with mass spectroscopy (col. A, 100°C) to contain several components, with masses greater than 800. The tube was washed out with ether and the ether evaporated, to give a brown residue (1.51g), which gave an orange oil (1.40g) on molecular distillation under reduced pressure. G.l.c. with mass spectroscopy (col. A, 150°C) showed this to contain two major components, only partially resolved, which were tentatively identified as $C_{11}F_{18}N_2$ (M^+ - F, 483) and $C_{10}F_{16}N_2$ (M^+ - F, 433). An analytical injection on a preparative scale instrument showed these to be unsatisfactorally resolved and the first peak to be made up of 4 smaller peaks. The mixture was not investigated further.

(j) Prolonged Photolysis of Perfluoro-2,5-di-s-butylpyrazine (151)

Perfluoro-2,5-di-s-butylpyrazine (151) (0.50g, 0.91 m.moles) was irradiated for 133 hours in a sealed silica tube. Only 0.05g of volatile product was obtained. Extraction of the tube with ether yielded a brown residue (0.37g). This was dissolved in pet. ether (60-80°C fraction) and insoluble material filtered off. On evaporating the solvent, a red oil remained (0.30g), with an i.r. spectrum similar to the oil obtained in the previous section. Its mass spectrum showed large peaks at 383 and 433.

(k) Mixture of Perfluoro-4-isopropylpyridazine (137) and Perfluoro-4-s-butylpyridazine (141)

The title compounds (137) (0.57g, 1.89 m.moles) and (141) (0.33g, 0.94 m.moles) were sealed in a silica tube (36 x 3.9cm) under high vacuum and irradiated for 96 hours. The volatile product (0.79g) was shown by g.l.c. and g.l.c. with mass spectroscopy to contain two components, identified by their mass spectra and g.l.c. retention times as perfluoro-2-isopropylpyrazine (146) (65% by wt.; 90% yield) and perfluoro-2-s-butylpyrazine (150) (35% by wt.; 84% yield).

(l) Mixture of Perfluoro-4,5-di-isopropylpyridazine (138) and Perfluoro-4,5-di-s-butylpyridazine (142)

The title compounds (138) (0.43g, 0.95 m.moles) and (142) (0.26g, 0.47 m.moles) were sealed in a silica tube (32 x 2.9cm) under high vacuum and irradiated for 30 hours. The volatile product (0.66g) was shown by g.l.c. and g.l.c. with mass spectroscopy (col. A, 90°C) to contain 4 major components, identified by their mass spectra and g.l.c. retention times as perfluoro-2,5-di-isopropylpyrazine (147) (56% by wt.; 99% yield); perfluoro-2,5-di-s-butylpyrazine (151) (8% by wt.; 56% yield); (138) (9% by wt.) and (142) (17% by wt.). Also visible were traces of perfluoro-2,6-di-s-butylpyrazine (153) and a defluorinated impurity (M^+,514), which was initially present in (142) but no cross-over products (M^+, 502) could be seen.

5. Photolysis of Perfluoro-4,5-di-s-butylpyridazine (142) at 300nm Under Transference

Perfluoro-4,5-di-s-butylpyridazine (142) (5.10g, 9.24 m.moles) was irradiated at 300nm in the Rayonet reactor, whilst under transference at 0.4mm pressure from a large silica vessel (39 x 10.5mm). The transference took 143 hours. The volatile product (4.85g) was shown by g.l.c. (col. A, 78°C) to contain perfluoro-4,5-di-s-butyl-1,2-diazabicyclo[2.2.0]-hexa-2,5-diene (142a) (34%); perfluoro-2,5-di-s-butylpyrazine (151) (7%); unknowns (8%); and starting material (142) (51%). The para-bonded species (142a) was obtained pure by fractional distillation under reduced pressure (4mm, b.p. 39-42°C), and identified by comparison of its ^{19}F n.m.r. spectrum with that of the authentic compound.[137]

A sample of (142a) was rearranged by passage through g.l.c. (col. A,50°C) to give a mixture, shown by n.m.r. to contain the 2,5-pyrazine (151) (ca. 20%) and perfluoro-1,4-di-s-butyl-2,5diazabicyclo[2.2.0]hexa-2,5-diene (142b) (ca. 80%).[137]

Both (142a) and (142b) were rearomatised by passing analytical samples through g.l.c. (col. A, 80°C), with an injector temperature of 300°C and gave only one peak, with a retention time corresponding to the 2,5-pyrazine (151).

6. Attempted Triplet Sensitization of Perfluoro-4,5-di-isopropylpyridazine (138)

Perfluoro-4,5-di-isopropylpyridazine (138) (1.38g, 3.05 m.moles) and benzophenone (0.59g, 3.24 m.moles) were dissolved in 20ml of Freon 113 and introduced into a silica tube (8 x 2.4cm). The solution was frozen in liquid air and the system evacuated, allowed to warm up to room temperature, and let down to atmospheric pressure with dry nitrogen. This was repeated twice and finally the tube was sealed under vacuum. The solution was then irradiated at 253.7nm in the Rayonet reactor for 48 hours, with the vapour phase shielded with metal foil. The solution was poured from the tube and the solvent evaporated, leaving an off-white solid (1.77g). Transference into a cold trap under vacuum gave a white solid, identified by g.l.c. and n.m.r. as unchanged (<u>138</u>) (73% recovery). The involatile oily residue (0.62g) had an i.r. spectrum showing only absorptions due to benzophenone.

X.B <u>PYROLYSIS EXPERIMENTS</u>

1. <u>Experimental Procedure</u>

A nickel tube was cleaned, dried in an oven and allowed to cool while being purged with dry nitrogen. The substrate was placed in the tube and the tube sealed, using copper washers, which had previously been annealed by heating to red heat in a flame and immersing immediately in ethanol. The tube was then placed in a furnace preheated to the required temperature and left there for 16 hours, after which time it was removed and allowed to cool. It was then frozen in liquid air and the top removed and replaced by a nozzle, through which the volatile products were pumped out into a trap in liquid air.

2. <u>Pyrolysis of Individual Pyridazine Derivatives</u>

(a) <u>Perfluoro-4,5-di-isopropylpyridazine (138)</u>

The results of a number of pyrolyses were summarised in Tables IX.1 and IX.2. One experiment is described fully below.

Perfluoro-4,5-di-isopropylpyridazine (<u>138</u>) (1.05g, 2.32 m.moles) was pyrolysed at 380°C. The volatile product (0.79g; 75% recovery) was shown by g.l.c. and g.l.c./mass spectroscopy (col. O, 95°C) to contain one major component (77%), which was separated by preparative g.l.c. and shown to be perfluoro-4,5-di-isopropylpyrimidine (<u>172</u>) by comparison of its ^{19}F n.m.r. and i.r. spectra with those of an authentic sample.[141] (^{19}F n.m.r. spectrum No.16; i.r.spectrum No.18). The original impurities were mainly two defluorinated compounds (M^+, 414), which were not isolated.

In the other experiments (138) was not isolated but the product mixtures were analysed by g.l.c. and g.l.c. with mass spectroscopy.

(b) Perfluoro-4,5-di-s-butylpyridazine (142)

The results of a number of pyrolyses were summarised in Table IX.3. The reaction mixtures were analysed by g.l.c. and g.l.c./mass spectroscopy (col. T, 83°C). They were separated by preparative g.l.c. to give pure samples of the two major products, which were:

(i) Perfluoro-2,5-di-s-butylpyrazine (151) (M^+, 552), identified by comparison with the sample obtained by photolysis of (142).

(ii) Perfluoro-4,5-di-s-butylpyrimidine (183), b.p. 174°C. (Found: C, 26.1; F, 68.3; N,5.5%; M^+, 552. $C_{12}F_{20}N_2$ requires C, 26.1; F, 68.8; N, 5.1%; M,552). λ_{max}(cyclohexane) 250nm (ε 4,000); ^{19}F n.m.r. spectrum No.17; i.r. spectrum No.19.

There were a large number of minor components, which included two defluorinated compounds (M^+, 514), two unknowns with $M^+ = 364$, and two with $M^+ = 602$. Others had uncountable mass spectra.

(c) Perfluoro-4-isopropyl-5-s-butylpyridazine (180)

The pyridazine (180) (1.12g, 2.23 m.moles) was pyrolysed at 300°C. The volatile product (0.93g) was shown by g.l.c. and g.l.c./mass spectroscopy (col. T, 90°C) to contain four major components A, B, C, and D in the ratio 3 : 44 : 43 : 4, all having $M^+ = 502$; and a large number of minor components (6%).

Compound A had a g.l.c. retention time and mass spectrum identical to perfluoro-2-isopropyl-5-s-butylpyrazine (181), obtained by photolysis of (180).

Compound D was starting material (180)

Compounds B and C were obtained pure by preparative g.l.c. (col. T, 65°C, 50µl injections). Compound B was identified as perfluoro-5-isopropyl-4-s-butylpyrimidine (184), b.p. 163°C. (Found: C, 26.4; F, 68.1; N, 5.4%; M^+, 502. $C_{11}F_{18}N_2$ requires C, 26.3; F,68.1; N, 5.6%; M, 502). λ_{max} (cyclohexane) 250nm (ϵ 3,900); ^{19}F n.mr. spectrum No.18; i.r. spectrum No.20.

Compound C was identified as perfluoro-4-isopropyl-5-s-butylpyrimidine (185), b.p. 163°C. (Found: C, 26.0; F, 68.0; N, 5.9%; M^+, 502). λ_{max} (cyclohexane) 250nm (ϵ 3,700); ^{19}F n.m.r. spectrum No.19; i.r. spectrum No. 21.

(d) Perfluoro-4-isopropylpyridazine (137)

Perfluoro-4-isopropylpyridazine (137) (1.34g, 4.44 m.moles) was pyrolysed at 400°C. The volatile product (1.08g, 81% recovery) was shown by g.l.c. and g.l.c./mass spectroscopy (col. O, 105°C) to contain two major components in the ratio 16 : 83, both with M^+ = 302. The second was (137). The major product was separated by preparative g.l.c. and shown by ^{19}F n.m.r. to be an approximately 3 : 4 mixture of perfluoro-4-isopropylpyrimidine (175) (n.m.r. spectrum No.20) and perfluoro-5-isopropylpyrimidine (174) (n.m.r. spectrum No.21).[141]

(e) Perfluoro-4-s-butylpyridazine (141)

(i) At 350°C

Perfluoro-4-s-butylpyridazine (141) (1.44g, 4.09 m.moles) was pyrolysed at 350°C. The volatile product (1.11g, 77% recovery) was shown by g.l.c. and g.l.c./mass spectroscopy (col. O, 100°C) to contain two major components, later identified as perfluoro-s-butylpyrimidine (32%) and starting material (141) (68%).

(ii) At 400°C

The pyridazine (141) (1.30g, 3.69 m.moles) was pyrolysed at 400°C and the volatile product (0.94g, 72% recovery) shown by g.l.c. and g.l.c./ mass spectroscopy to contain a defluorinated compound (M^+, 314; 6% by wt.) and perfluoro-s-butylpyrimidine (M^+, 352; 94% by wt.).

The combined product from both pyrolyses was separated by preparative g.l.c. (col. O, 105°C) to obtain the perfluoro-s-butylpyrimidine. (Found: C, 27.5; F, 64.4; N, 8.3%; M^+, 352. $C_8F_{12}N_2$ requires C, 27.3; F, 64.8; N, 8.0%; M, 352). ^{19}F n.m.r. showed this to be an approximately 1 : 1 mixture of perfluoro-4-s-butylpyrimidine (187)[146] (n.m.r. spectrum No.22) and the new compound perfluoro-5-s-butylpyrimidine (186) (n.m.r. spectrum No.23) but they could not be separated.

(f) Tetrafluoropyridazine (136)

When tetrafluoropyridazine (136) (1.32g, 8.68 m.moles) was pyrolysed at 300°C, 1.01g (77%) was recovered unchanged. Similarly, pyrolysis of (136) (2.15g, 14.1 m.moles) at 350°C gave 1.85g (86% recovery) of (136), over 99% pure by g.l.c.

(g) 4,5-Dichlorodifluoropyridazine (167)

Pyrolysis of 4,5-dichlorodifluoropyridazine (167) (1.47g, 7.95 m.moles) at 300°C yielded 1.36g (93% recovery) of unchanged (167). Pyrolysis of (167) (1.40g, 7.57 m.moles) at 350°C yielded 1.01g (72% recovery) of unchanged (167).

3. Pyrolysis of Mixtures

(a) Perfluoro-4,5-di-isopropylpyridazine (138) and Perfluoro-4,5-di-s-butylpyridazine (142)

(i) At 350°C

The title compounds (138) (1.20g, 2.65 m.moles) and (142) (1.51g, 2.73

m.moles) were pyrolysed together at 350°C. The volatile product (2.42g, 89% recovery) was shown by g.l.c. and g.l.c./mass spectroscopy (col. T, 80°C and col. O, 100°C) to contain perfluoro-2,5-di-s-butylpyrazine (151) (M^+, 552; 7.5% by wt.); perfluoro-4,5-di-isopropylpyrimidine (172) (M^+, 452; 46% by wt.); perfluoro-4,5-di-s-butylpyrimidine (183) (M^+, 552; 40% by wt.); and several unknowns. No cross-over products with M^+ = 502 were observed.

(ii) At 300°C

The title compounds (138) (1.03g, 2.28m.moles) and (142) (1.25g, 2.26 m.moles) were pyrolysed together at 300°C. The volatile product (1.94g, 85% recovery) was shown as above to contain (151) (2.5% by wt.); (172) (44%); (183) (45%); (138) (4%); (142) (2%); and several unknowns.

(b) Perfluoro-4,5-di-s-butylpyridazine (142) and Tetrafluoropyridazine (136) at 300°C

(i) 1 : 1 Mixture

The title compounds (142) (1.96g, 3.55 m.moles) and (136) (0.53g, 3.49 m.moles) were pyrolysed together at 300°C. The volatile product (2.09g, 84% recovery) was shown by g.l.c. and g.l.c./mass spectroscopy (col. T, 90 and 150°C) to contain perfluoro-2,5-di-s-butylpyrazine (151) (M^+, 552; 6.5% by wt.); perfluoro-4,5-di-s-butylpyrimidine (183) (M^+, 552; 70%); (142) (M^+, 552; 1.5%); tetrafluoropyrimidine (171) (M^+, 152; 6.5%); (136) (M^+, 152; 13.5%); and some unidentified impurities.

(ii) 1 : 4 Mixture

The title compounds (142) (1.19g, 2.16 m.moles) and (136) (1.32g, 8.68 m.moles) were pyrolysed at 300°C. The volatile product (2.20g, 80% recovery) was shown as above to contain (151) (4% by wt.); (183) (40%); (142) (2%); (171) (15%); (136) (38%); and some minor, unidentified impurities.

(iii) 1 : 10 Mixture

The title compounds (142) (0.67g, 1.21 m.moles) and (136) (1.86g, 12.24 m.moles) were pyrolysed at 300°C. The volatile product (1.69g, 67% recovery) was shown as before to contain (151) (2% by wt.); (183) (19.5%); (142) (3%); (171) (16%); (136) (59%); and minor impurities.

(iv) 1 : 1 Mixture in a Pyrex Tube

The title compounds (142) (1.15g, 2.08m.moles) and (136) (0.31g, 2.04 m.moles) were sealed at atmospheric pressure in a pyrex tube filled with dry nitrogen and pyrolysed at 300°C. The volatile product (1.17g, 80% recovery) was shown as before to contain (151) (5% by wt.); (183) (69%); (142) (6%); (171) (4%); (136) (8%); and several unknowns.

The product mixtures from the four experiments above were separated by preparative g.l.c. (col. O, 130°C) and the identity of the tetrafluoropyrimidine (171) confirmed by its i.r. spectrum.

(c) Perfluoro-4,5-di-s-butylpyridazine (142) and 4,5-Dichlorodifluoropyridazine (167) at 300°C

The title compounds (142) (1.18g, 2.14 m.moles) and (167) (0.73g, 3.95 m.moles) were pyrolysed at 300°C. The volatile product (1.74g, 91% recovery) was shown by g.l.c. and g.l.c/mass spectroscopy (col. O, 140°C) to contain a peak due to unresolved perfluoro-2,5-di-s-butylpyrazine (151) and perfluoro-4,5-di-s-butylpyrimidine (183) (M^+, 552; 21% by wt.); (142) (45%); a compound tentatively identified as 4,5-dichlorodifluoropyrimidine (M^+, 184; 5%); and (167) (29%).

(d) Other Mixtures Containing Tetrafluoropyridazine (136)

(i) With Perfluoro-1-methyldecalin at 300°C

Tetrafluoropyridazine (136) (1.59g, 10.56 m.moles) and perfluoro-1-methyldecalin (6.79g, 13.26 m.moles) were pyrolysed at 300°C and the volatile product (8.02g, 96% recovery) was shown by g.l.c. (cols. T and O, various temperatures) to contain only unchanged starting materials.

(ii) With Perfluoro-4,5-di-s-butylpyrimidine (183) at 300°C

Tetrafluoropyridazine (136) (1.51g, 9.93 m.moles) and the pyrimidine (183) (0.46g, 0.83 m.moles) were pyrolysed at 300°C. The volatile product (1.69g, 86% recovery) was shown by g.l.c. (col. O, 100°C) to contain only unchanged starting materials.

(iii) With Perfluoro-2,5-di-s-butylpyrazine (151) at 300°C

Tetrafluoropyridazine (136) (1.55g, 10.2 m.moles) and the pyrazine (151) (0.75g, 1.36 m.moles) were pyrolysed at 300°C. The volatile product (2.16g, 94% recovery) was shown by g.l.c. (col. O, 100°C) to contain only unchanged starting materials.

(iv) With Perfluoro-2,5-di-isopropylpyrazine (147) at 300°C

Tetrafluoropyridazine (136) (1.42g, 9.34 m.moles) and the pyrazine (147) (0.57g, 1.26 m.moles) were pyrolysed at 300°C and the volatile product (1.80g, 90% recovery) shown by g.l.c. (col. T, 140°C) to contain only unchanged starting materials.

(v) With Perfluoro-4-isopropyl-5-s-butylpyridazine (180) at 300°C

Tetrafluoropyridazine (136) (1.44g, 9.47 m.moles) and the pyridazine (180) (0.69g, 1.37 m.moles) were pyrolysed at 300°C. The volatile product (2.04g, 96% recovery) was shown by g.l.c. and g.l.c./mass spectroscopy (col. T, 140°C) to contain perfluoro-2-isopropyl-5-s-butylpyrazine (M^+, 502; 1% by wt.); perfluoro-4-isopropyl-5-s-butylpyrimidine (185) and perfluoro-5-isopropyl-4-s-butylpyrimidine (184) (M^+, 502; total: 25%); (180) (8%); tetrafluoropyrimidine (171) (M^+, 152; 12%); and (136) (54%).

(vi) With Perfluoro-4,5-di-isopropylpyridazine (138) at 300°C

Tetrafluoropyridazine (136) (1.43g, 9.41 m.moles) and (138) (1.06g, 2.34 m.moles) were pyrolysed at 300°C. The volatile product (2.22g, 89% recovery) was shown by g.l.c. (col. O, 100°C) to contain mainly (138) (48% by wt.) and (136) (52%), with only a trace of perfluoro-4,5-di-isopropylpyrimidine (172).

(vii) With Perfluoro-4,5-di-isopropylpyridazine (138) at 350°C

Tetrafluoropyridazine (136) (1.55g, 10.2 m.moles) and (138) (0.47g, 1.04 m.moles) were pyrolysed at 350°C. The volatile product (1.78g, 88% recovery) was shown by g.l.c. (col. O, 100°C ; col. T, 150°C) to contain no tetrafluoropyrimidine (171), and the ratio of perfluoro-4,5-di-isopropylpyrimidine (172) to (138) was 7 : 93.

(e) Perfluoro-4,5-di-isopropylpyridazine (138) With Inert Solvents

(i) With Perfluoro-1-methyldecalin at 350°C

The pyridazine (138) (0.51g, 1.13 m.moles) and perfluoro-1-methyldecalin (5.73g, 11.19 m.moles) were pyrolysed at 350°C. The volatile product (6.14g, 98% recovery) was shown by g.l.c./mass spectroscopy (col. T, 90°C) to contain mainly perfluoro-1-methyldecalin, with perfluoro-4,5-di-isopropylpyrimidine (172) and (138) in the ratio 86 : 14.

(ii) With Hexafluorobenzene (28) at 350°C

The pyridazine (138) (0.51g, 1.13 m.moles) and hexafluorobenzene (28) (2.05g, 11.0 m.moles) were pyrolysed at 350°C. The volatile product (2.47g, 96% recovery) was shown by g.l.c. and g.l.c./mass spectroscopy (col. Z, 100°C) to contain mainly (28), with perfluoro-4,5-di-isopropylpyrimidine (172) and (138) in the ratio 5 : 95.

N.B. Both perfluoro-1-methyldecalin and hexafluorobenzene were recovered unchanged on pyrolysis separately at 350°C.

(f) Perfluoro-4-s-butylpyridazine (141) and Perfluoro-4-isopropylpyridazine (137) at 400°C

The title compounds (141) (0.38g, 1.08 m.moles) and (137) (1.26g, 4.17 m.moles) were pyrolysed at 400°C. The volatile product (1.08g, 66% recovery) was shown by g.l.c. and g.l.c./mass spectroscopy (col. O, 100°C) to contain perfluoro-isopropylpyrimidines (M^+, 352; 24% by wt.); perfluoro-s-butylpyrimidines (M^+, 352; 10.5%); (137) (46%); and (141) (19.5%).

(g) ^{15}N-Labelled Perfluoro-4,5-di-isopropylpyridazine (138) and Unlabelled Perfluoro-4,5-di-s-butylpyridazine (142) at 300°C

A 50/50 mixture of doubly ^{15}N-labelled (138) and unlabelled (138) (0.09g, 0.20 m.moles) was dissolved in unlabelled (142) (0.54g, 0.98 m.moles) and the mixture examined by g.l.c./mass spectroscopy (col. O, 125°C). Compound (138) showed parent peaks at 452 and 454, of roughly equal size. Some of the mixture (0.58g) was pyrolysed at 300°C and the volatile product (0.31g, 53% recovery) was examined by g.l.c./mass spectroscopy (col.A, 90°C). The perfluoro-4,5-di-isopropylpyrimidine (172) present showed parent peaks at 452 and 454, of roughly equal size, and no significant peak at 453. The perfluoro-4,5-di-s-butylpyrimidine (183) showed no increased P + 1 (553).

X.C PREPARATION OF PYRIDAZINE DERIVATIVES

1. General

(a) Reagents

Tetrafluoropyridazine was prepared by technical staff, by the route given in Chapter IX.

Caesium fluoride, potassium fluoride and lithium chloride were dried by alternately heating to 150°C under high vacuum for several hours and crushing to a fine powder. They were stored under dry nitrogen.

The solvents were described in Chapter VI.

The perfluoro-olefins were supplied by Bristol Organics Ltd.

^{15}N-labelled hydrazine was obtained from Prochem Ltd.

(b) Procedure for Polyfluoroalkylation Reactions

Caesium fluoride and sulpholane were introduced into the reaction vessel, which had been baked and purged with dry nitrogen, against a stream of dry nitrogen. The reaction vessel was fitted with a football bladder, which acted as a variable volume gas reservoir. The apparatus was evacuated and the required amount of gaseous perfluoro-olefin introduced into it. Tetrafluoropyridazine (136) was rapidly introduced into the reaction mixture, which was stirred vigorously during the reaction. Collapse of the bladder and colouration of the reaction mixture occurred during the reaction. On completion, the products were removed by transference under vacuum at 90°C into a trap cooled in liquid air.

2. Preparation of Perfluoroalkylpyridazines

Most of these reactions were performed on several occasions and only one example of each is described.

(a) Perfluoro-4,5-di-isopropylpyridazine (138)

A mixture of caesium fluoride (6.5g, 42.8 m.moles),sulpholane (40ml), hexafluoropropene (44) (16.6g, 110.5 m.moles), and tetrafluoropyridazine (136) (8.0g, 52.6 m.moles) was stirred at room temperature for 5 hours, after which time a partial vacuum had formed in the apparatus. The volatile product (23.18g) was recrystallised from hexane and identified as perfluoro-4,5-di-isopropylpyridazine (138) (19.29g, 81% yield) by comparison of its i.r. and ^{19}F n.m.r. spectra with those of an authentic sample.[148]

(b) Perfluoro-4,5-di-s-butylpyridazine (142)

A mixture of caesium fluoride (4.2g, 27.6 m.moles), sulpholane (50ml), octafluoro-but-2-ene (77) (26.2g, 131.0 m.moles), and tetrafluoropyridazine (136) (9.68, 63.7 m.moles) was stirred at 60°C for 40 hours. Not all of the octafluorobut-2-ene was absorbed. The volatile product

(28.10g) was shown by g.l.c. and g.l.c./mass spectroscopy (col. T, 90°C) to contain butene oligomers (6% by wt.); perfluoro-3,5-di-s-butylpyridazine (M^+, 552), contaminated with defluorinated compounds (M^+, 514) (total: 6%); perfluoro-4,5-di-s-butylpyridazine (142) (72%, 58% yield); and perfluoro-4-s-butylpyridazine (141) (16%, 20% yield). The latter two compounds were obtained pure by preparative g.l.c. (col. T, 100°C) and identified by comparison of their i.r. and ^{19}F n.m.r. spectra with those of authentic samples.[146]

(c) Perfluoro-4-isopropylpyridazine (137)

A mixture of caesium fluoride (3.2g, 21.1 m.moles), sulpholane (65ml), perfluoro-4,5-di-isopropylpyridazine (10g, 22.1 m.moles) and tetrafluoropyridazine (136) (4.0g, 26.3 m.moles) was stirred at 120°C for 17 hours. The volatile product (10.71g) was shown by g.l.c. and g.l.c./mass spectroscopy (col. A, 100°C) to contain perfluoro-3,5-di-isopropylpyridazine (11% by wt., 6% yield) and perfluoro-4-isopropylpyridazine (137) (89%, 71% yield). Compound (137) was purified by fractional distillation on a small concentric tube Fischer Spoltrohr System M.M.S. 200, (b.p. 143-145°C), and identified by comparison of its i.r. and n.m.r. spectra with those of an authentic sample.[148]

(d) Perfluoro-4-s-butylpyridazine (141)

A mixture of caesium fluoride (5.0g, 32.9 m.moles), sulpholane (10ml), perfluoro-4,5-di-s-butylpyridazine (142) (12.17g, 22.05 m.moles) and tetrafluoropyridazine (136) (4.78g, 31.44 m.moles) was stirred at 80°C for 4 days. The volatile product (10.77g) was shown by g.l.c. and g.l.c./mass spectroscopy (col. T, 90°C) to contain perfluoro-3,5-di-s-butylpyridazine (M^+, 552; 9% by wt., 5% yield); perfluoro-4,5-di-s-butylpyridazine (142) (26%); and perfluoro-4-s-butylpyridazine (141) (65%, 59% yield). Compound (141) was obtained 99% pure by fractionation on the small concentric tube (b.p. 154-155°C) and identified by comparison of its i.r. and n.m.r. spectra with those of an authentic sample.[146]

(e) Perfluoro-4-isopropyl-5-s-butylpyridazine (180)

A mixture of caesium fluoride (3.3g, 21.7 m.moles), sulpholane (10ml), hexafluoropropene (44) (5.7g, 37.9 m.moles), and perfluoro-4-s-butylpyridazine (141) (9.34g, 26.5 m.moles) was stirred at room temperature for 2 hours. The volatile product (13.84g) was shown by g.l.c. (col. T, 100°C) to be one major component (93%), which was separated by preparative g.l.c. (col. T, 115°C) and identified as perfluoro-4-isopropyl-5-s-butylpyridazine (180) (97% yield), b.p. 177°C. (Found: C, 26.1; F, 67.8; N, 6.0%; M^+, 502. $C_{11}F_{18}N_2$ requires C, 26.3; F, 68.1; N, 6.6%; M,502). λ_{max} (cyclohexane) 279nm (ϵ 4,700), 340nm (ϵ 370); ^{19}F n.m.r. spectrum No.24; i.r. spectrum No.22.

3. Preparation of 4,5-Dichlorodifluoropyridazine (167)

A mixture of tetrafluoropyridazine (136) (8.30g, 54.6 m.moles), lithium chloride (8.90g, 209.9 m.moles) and D.M.F. (40ml) was stirred at 100°C for ca. 45 minutes, giving a yellow solution. This was quenched with iced water and ether extracted several times. The extracts were washed thoroughly, dried ($MgSO_4$), and the solvent distilled off. The residue was sublimed under reduced pressure (0.5mm, 44°C) to give a white solid (8.10g), identified as 4,5-dichlorodifluoropyridazine (136) (80% yield) by comparison with an authentic sample.[149]

4. Preparation of ^{15}N-Labelled Perfluoro-4,5-di-isopropylpyridazine (138)

(a) Labelled 4,5-Dichlorodihydroxypyridazine

An aqueous solution containing 95.4% ^{15}N-labelled hydrazine (0.23g, 6.76 m.moles) was diluted to about 15ml with distilled water and acidified with a few drops of conc. H_2SO_4. To this was added dichloromaleic anhydride (1.20g, 7.19 m.moles) and the mixture was stirred for 2 hours at room temperature and 2 hours at 100°C. The product was allowed to cool overnight and the solid filtered off, washed with a little cold water and dried in an oven. This was identified as 4,5-dichlorodihydroxypyridazine (1.01g, 82% yield) by comparison of its i.r. spectrum with that of the authentic unlabelled compound.

(b) Chlorination of 4,5-Dichlorodihydroxypyridazine

The sample obtained above (1.01g) was added to some of the unlabelled compound (0.99g) and placed in a nickel tube with 20ml of phosphoryl chloride (freshly distilled). The tube was sealed and placed in a furnace, preheated to 140°C, for 4 hours. After cooling, the contents were poured from the tube and excess phosphoryl chloride pumped off. The tube was washed out with iced water, which was then neutralised with sodium carbonate and added to the involatile residue from above. The tube was then washed out with methylene chloride and the washings used to extract the mixture above. This was extracted thoroughly with more methylene chloride and the extracts combined, washed, dried ($MgSO_4$), and the solvent removed under vacuum to leave an off-white solid (2.31g) The solid was sublimed under reduced pressure (0.05mm, 80°C) to give a white sublimate, identified as tetrachloropyridazine (166) (2.01g, 84% yield) from its i.r. spectrum.

(c) Fluorination and Subsequent Polyfluoroalkylation of Tetrachloropyridazine (166)

The tetrachloropyridazine (166) from above (2.01g, 9.18 m.moles) was mixed with dry potassium fluoride (12.02g, 206.9 m.moles) and sealed in a nickel tube. This was placed in a furnace, preheated to 360°C, for 2½ hours. The tube was cooled and the volatiles pumped into a trap, when very little tetrafluoropyridazine (136) could be seen. The contents were pumped into a reaction vessel prepared for the polyfluoroalkylation reaction, containing caesium fluoride (1.7g, 11.2 m.moles), sulpholane (5ml), and hexafluoropropene (44) (3.06g, 20.4 m.moles). The mixture was stirred overnight, after which time the bladder was deflated. The volatile product (3.92g) was shown by g.l.c. to contain mainly oligomers of (44). These were removed by warming in the air, to leave a damp solid (1.05g), smelling strongly of sulpholane. This was recrystallised from hexane to give perfluoro-4,5-di-isopropylpyridazine (138) (0.09g, 2% yield), which was immediately added to some unlabelled perfluoro-4,5-di-s-butylpyridazine (142) (0.54g) and investigated by g.l.c./mass spectroscopy (col. O, 125°C). The labelled (138) showed parent peaks at 452 and 454 of approximately equal size, as expected, showing it to be a 50/50 mixture of unlabelled and doubly ^{15}N-labelled compound.

APPENDICES

APPENDIX I

N.M.R. SPECTRA

Index

1. Octafluoro-4,4'-bipyridyl (56).
2. 4-H-tetrafluoropyridine (61).
3. Octachloro-4,4'-bipyridyl (65).
4. 4-H-tetrachloropyridine (63).
5. Heptachlorobipyridyl (66).
6. 2-H-heptafluoropropane (87).
7. Octafluoro-4,4'-dimethoxybiphenyl (113).
8. Hexafluoro-2,2'-dihydro-4,4'-dimethoxybiphenyl (114).
9. Perfluoro-2,5-di-isopropylpyrazine (147).
10. Perfluoro-2-isopropylpyrazine (146).
11. Perfluoro-2-s-butylpyrazine (150).
12. Perfluoro-2,5-di-s-butylpyrazine (151).
13. Perfluoro-2,6-di-s-butylpyrazine (153).
14. Perfluoro-2-isopropyl-5-s-butylpyrazine (181).
15. Perfluoro-2-isopropyl-6-s-butylpyrazine (182).
16. Perfluoro-4,5-di-isopropylpyrimidine (172).
17. Perfluoro-4,5-di-s-butylpyrimidine (183).
18. Perfluoro-5-isopropyl-4-s-butylpyrimidine (184).
19. Perfluoro-4-isopropyl-5-s-butylpyrimidine (185).
20. Perfluoro-4-isopropylpyrimidine (175).
21. Perfluoro-5-isopropylpyrimidine (174).
22. Perfluoro-4-s-butylpyrimidine (187).

23. Perfluoro-5-s-butylpyrimidine (186).

24. Perfluoro-4-isopropyl-5-s-butylpyridazine (180).

Abbreviations

The following abbreviations have been used in the tabulation :

S = singlet

D = doublet

T = triplet

Q = quartet

Sext = sextet

Sept = septet

M = multiplet

Shift p.p.m.	Fine Structure Coupling Constants in Hz.	Relative Intensity	Assignment
1. Octafluoro-4,4'-bipyridyl (56)			
88.4	M	1	2,2',6,6'
139.7	M	1	3,3',5,5'

The spectrum was recorded in CCl_4 solution on the Varian spectrometer, with an external $CFCl_3$ reference.

2. 4-H-tetrafluoropyridine (61)

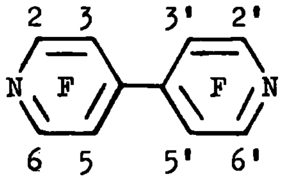
^{19}F			
95.7	Broad	1	2,6
143.9	M	1	3,5
^{1}H			
7.47	M		

The spectra were recorded neat on the Varian spectrometer, with external $CFCl_3$ and T.M.S. as references.

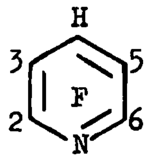
3. Octachloro-4,4'-bipyridyl (65)

^{13}C			
128.1	M	2	
144.7	M	1	4,4'
146.8	M	2	

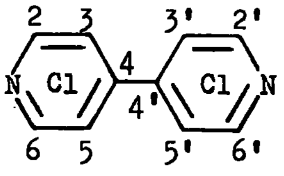
The spectrum was recorded in $CDCl_3$ soln. on the Brüker spectrometer, with external T.M.S. reference.



(56)



(61)



(65)

Shift p.p.m.	Fine Structure Coupling Constants in Hz.	Relative Intensity	Assignment
4. <u>4-H-tetrachloropyridine (63)</u>			
7.86	S		

The spectrum was recorded in CCl_4 soln. on the Varian spectrometer, with an internal T.M.S. reference.

5. <u>Heptachlorobipyridyl (66)</u>			
7.08	S		

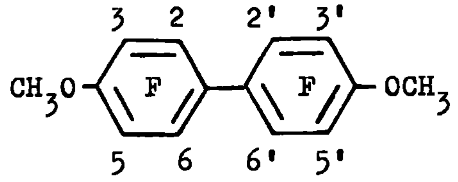
The spectrum was recoreded in CCl_4 soln. on the Varian spectrometer, with an internal T.M.S. reference.

6. <u>2-H-heptafluoropropane (87)</u>	$\overset{1}{CF_3}\overset{2}{CFH}\overset{1}{CF_3}$		
<u>^{19}F</u>			
77.5	$D(J_{1,2} = 11.3)$ of $D(J_{1,H} = 5.6)$	6	1
215.1	$D(J_{2,H} = 45)$ of $Sept(J_{2,1} = 11.3)$	1	2
<u>^{1}H</u>			
5.14	$D(J_{H,2} = 45)$ of $Sept(J_{H,1} = 5.6)$		

The spectra were recorded in a sealed n.m.r. tube with $CDCl_3$ on the Varian spectrometer, with external $CFCl_3$ and T.M.S. as references.

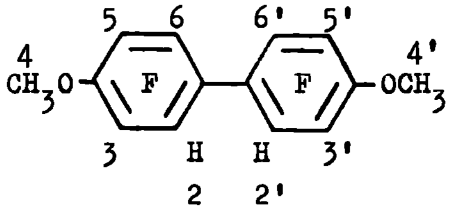
7. <u>Octafluoro-4,4'-dimethoxybiphenyl (113)</u>			
<u>^{19}F</u>			
140.1	M	1	2,2',6,6'
157.6	M	1	3,3',5,5'
<u>^{1}H</u>			
4.59	Broad S		OCH_3

(<u>113</u>)



Shift p.p.m.	Fine Structure Coupling Constants in Hz.	Relative Intensity	Assignment

8. Hexafluoro-2,2'-dihydro-4,4'-dimethoxybiphenyl (114)



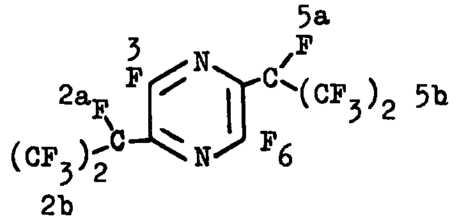
(114)

^{19}F			
133.6	M	1	3,3'
141.7	M	1	6,6'
150.7	M	1	5,5'
^{1}H			
4.56	$T(J_{4,5} = J_{4,3} = 1.3)$	3	4,4'
7.38	Broad M	1	2,2'

Spectra 7 and 8 were recorded in $CDCl_3$ soln. on the Varian spectrometer, with external $CFCl_3$ and T.M.S. as references.

9. Perfluoro-2,5-di-isopropylpyrazine (147)

73.8	Broad D	1	3,6
76.3	M	6	2b,5b
186.6	Broad	1	2a,5a

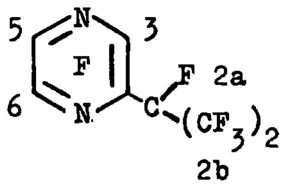


(147)

The spectrum was recorded neat on the Varian spectrometer, with an external $CFCl_3$ reference.

Shift p.p.m.	Fine Structure Coupling Constants in Hz.	Relative Intensity	Assignment
10. <u>Perfluoro-2-isopropylpyrazine (146)</u>			
77.1	M	7	2b,3
83.9	Broad D($J_{5,6}$ = 19)	1	5
93.7	D($J_{6,3}$ = 45) of D($J_{6,5}$ = 19)	1	6
186.8	Broad D($J_{2a,3}$ = 45)	1	2a

(<u>146</u>)

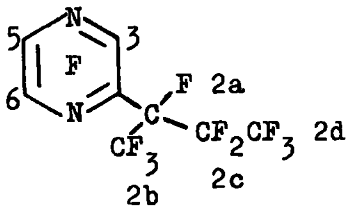


The spectrum was recorded neat on the Varian spectrometer, with an external $CFCl_3$ reference.

11. <u>Perfluoro-2-s-butylpyrazine (150)</u>

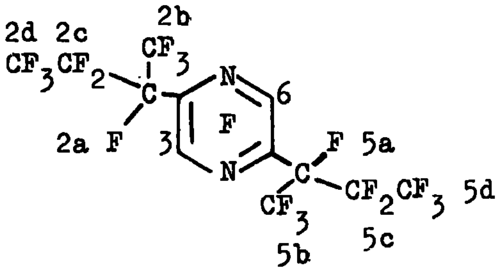
73.1	S	3	2b
75.9	M	1	3
80.7	Broad	3	2d
82.1	D($J_{5,6}$ = 20) of D($J_{5,3}$ = 5)	1	5
91.6	D($J_{6,3}$ = 45) of D($J_{6,5}$ = 20)	1	6
120.4	Complex M	2	2c
185.7	Broad D($J_{2a,3}$ = 54)	1	2a

(<u>150</u>)



The spectrum was recorded in $CDCl_3$ soln. on the Brüker spectrometer, with an internal $CFCl_3$ reference.

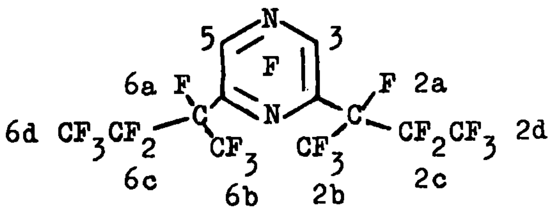
Shift p.p.m.	Fine Structure Coupling Constants in Hz.	Relative Intensity	Assignment
12.	**Perfluoro-2,5-di-s-butylpyrazine (151)**		
73.2	S	3	2b,5b
75.3	D	1	3,6
80.9	M	3	2d,5d
120.8	AB System($J_{2c',2c''}$ = 282)	2	2c,5c
186.6	Broad	1	2a,5a



(151)

The spectrum was recorded neat in a sealed capillary, on the Brüker spectrometer, with an external $CFCl_3$ reference.

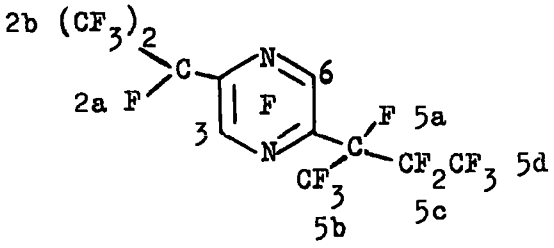
Shift p.p.m.	Fine Structure Coupling Constants in Hz.	Relative Intensity	Assignment
13.	**Perfluoro-2,6-di-s-butylpyrazine (153)**		
67.0	D($J_{3,2a}$ = 52)	1	3,5
75.3	S	3	2b,6b
83.2	M	3	2d,6d
122.8	AB System($J_{2c',2c''}$ = 290)	2	2c,6c
188.7	Broad D($J_{2a,3}$ = 52)	1	2a,6a



(153)

The spectrum was recorded neat in a sealed capillary on the Brüker spectrometer, with external $CFCl_3$ as reference.

Shift p.p.m.	Fine Structure Coupling Constants in Hz.	Relative Intensity	Assignment
14. <u>Perfluoro-2-isopropyl-5-s-butylpyrazine (181)</u>			
74.2	Broad S	3	5b
76.0	Broad	1	3 or 6
76.4	M	6	2b
76.8	Broad	1	3 or 6
82.3	Complex M	3	5d
121.4	Complex M	2	5c
187.0	Broad	2	2a,5a

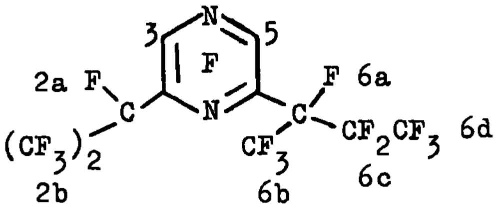


(<u>181</u>)

The spectrum was recorded neat on the Varian spectrometer, with an external $CFCl_3$ reference.

15. <u>Perfluoro-2-isopropyl-6-s-butylpyrazine (182)</u>

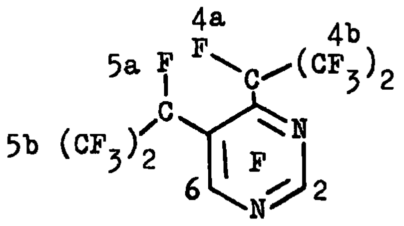
65.1	D(J = ca. 60) } Overlapping	2	3,5
65.9	D(J = ca. 60)		
73.9	S	3	6b
76.1	S	6	2b
81.6	S	3	6d
121.2	AB System($J_{6c',6c''}$ = 296)	2	6c
186.3	D(J = ca. 60) } Overlapping	2	2a,6a
187.3	D(J = ca. 60)		



(<u>182</u>)

The spectrum was recorded neat in a sealed capillary on the Brüker spectrometer, with an external $CFCl_3$ reference.

Shift p.p.m.	Fine Structure Coupling Constants in Hz.	Relative Intensity	Assignment
16. Perfluoro-4,5-di-isopropylpyrimidine (172)			
36.7	M	1	6
38.2	S	1	2
72.2	D	6	4b
74.0	D	6	5b
172.3	AB System($J_{4a,5a}$ = 198)	2	4a,5a

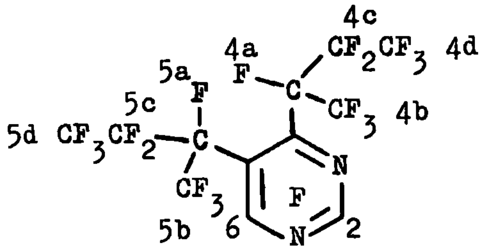


(172)

The spectrum was recorded neat in a sealed capillary on the Brüker spectrometer, with an external $CFCl_3$ reference.

Shift p.p.m.	Fine Structure Coupling Constants in Hz.	Relative Intensity	Assignment
17. Perfluoro-4,5-di-s-butylpyrimidine (183)			
36.8	M	1	6
40.1	S	1	2
71.6	S	3	4b
73.9	Broad	3	5b
75.3	Broad		
81.8	Broad	6	4d,5d
116.9	Complex M	4	4c,5c
175.4	Broad	2	4a,5a

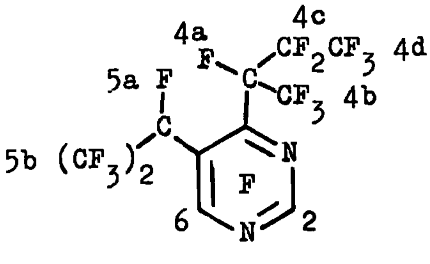
On heating to 140°C the two signals due to 5b merge to give a broad resonance at 74.3 p.p.m.



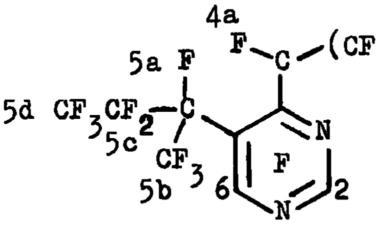
(183)

The spectrum was recorded neat on the Varian spectrometer, with an external $CFCl_3$ reference.

Shift p.p.m.	Fine Structure Coupling Constants in Hz.	Relative Intensity	Assignment
18. <u>Perfluoro-5-isopropyl-4-s-butylpyrimidine (184)</u>			
35.8	Sept($J_{6,5b}$ = 30)	1	6
37.3	S	1	2
69.0	S	3	4b
72.3	D($J_{5b,6}$ = 30)	3	5b'
73.7	Broad	3	5b''
78.8	S	3	4d
114.3	AB System($J_{4c',4c''}$ = 295)	2	4c
171.5	AB System($J_{4a,5a}$ = 202)	2	4a,5a



(<u>184</u>)



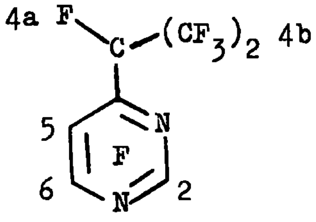
(<u>185</u>)

19. <u>Perfluoro-4-isopropyl-5-s-butylpyrimidine (185)</u>

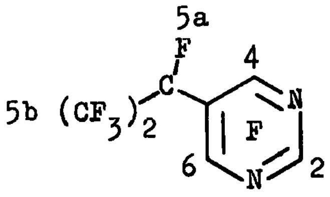
34.3	Sext($J_{6,5b}$ = $J_{6,5c}$ = 34)	1	6
36.9	S	1	2
71.1	S	6	4b
72.1	Broad D($J_{5b,6}$ = 28)	3	5b
79.4	S	3	5d
113.2	D($J_{5c',5c''}$ = 300) of D($J_{5c',6}$ = 38) of M	1	5c'
116.3	D($J_{5c'',5c'}$ = 300) of D($J_{5c'',6}$ = 38) of Q($J_{5c'',5b}$ = 14)	1	5c''
172.7	S	2	4a,5a

Spectra 18 and 19 were recorded neat in sealed capillaries on the Brüker spectrometer, with an external $CFCl_3$ reference.

Shift p.p.m.	Fine Structure Coupling Constants in Hz.	Relative Intensity	Assignment
20. Perfluoro-4-isopropylpyrimidine (175)			
46.2	D	1	2
70.3	D	1	6
76.2	S	6	4b
152.6	Broad	1	5
186.9	D	1	4a
21. Perfluoro-5-isopropylpyrimidine (174)			
38.2	S	1	2
45.1	Broad S	2	4,6
77.6	M	6	5b
180.6	T	1	5a



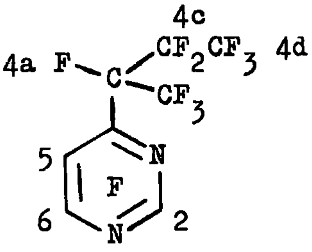
(175)



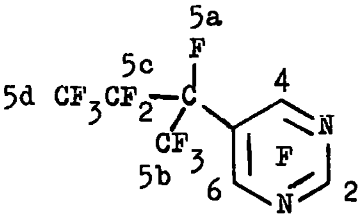
(174)

Spectra 20 and 21 were run on an approximately 3 : 4 mixture of (175) and (174) in a sealed capillary on the Brüker spectrometer, with an external $CFCl_3$ reference.

Shift p.p.m.	Fine Structure Coupling Constants in Hz.	Relative Intensity	Assignment
22. <u>Perfluoro-4-s-butylpyrimidine (187)</u>			
46.2	D	1	2
70.6	D	1	6
74.1	S	3	4b
82.2	Complex M	3	4d
121.6	Complex M	2	4c
153.0	Broad	1	5
187.7	D	1	4a



(<u>187</u>)



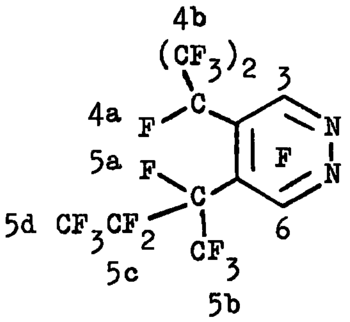
(<u>186</u>)

23. <u>Perfluoro-5-s-butylpyrimidine (186)</u>			
38.4	S	1	2
43.7	Broad	1	4 or 6
45.4	Broad	1	4 or 6
75.3	S	3	5b
82.2	Complex M	3	5d
121.6	Complex M	2	5c
182.7	D	1	5a

Spectra 22 and 23 were run on an approximately 1 : 1 mixture of (<u>187</u>) and (<u>186</u>) in a sealed capillary on the Brüker spectrometer, with an external $CFCl_3$ reference.

Shift p.p.m.	Fine Structure Coupling Constants in Hz.	Relative Intensity	Assignment
24. Perfluoro-4-isopropyl-5-s-butylpyridazine (180)			
69.9	M	2	3,6
73.1 73.8	Complex M	9	4b,5b
82.0	M	3	5d
115.2	Complex M	2	5c
170.3	AB System($J_{4a,5a}$ = 227)	2	4a,5a

The coupling between 4a and 5a is invariant at up to 160°C.



(180)

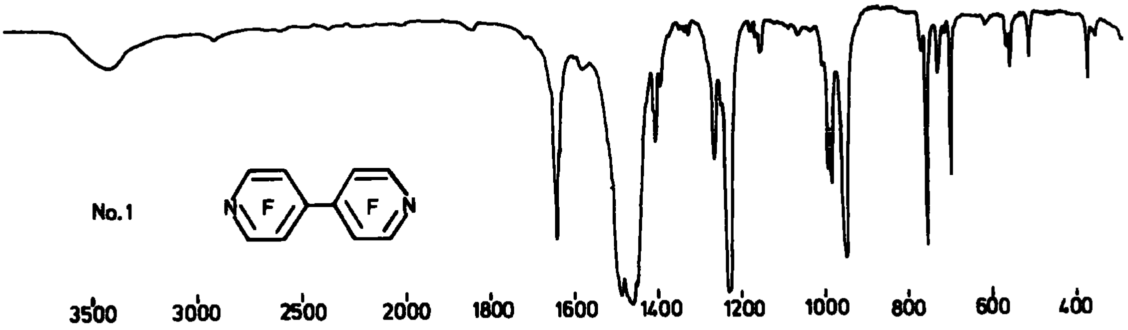
The spectrum was recorded neat on the Varian spectrometer, with an external $CFCl_3$ reference.

APPENDIX II

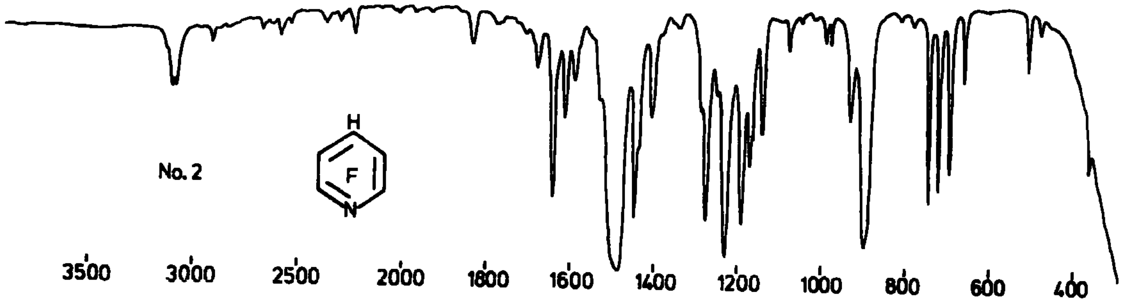
INFRA-RED SPECTRA

Index

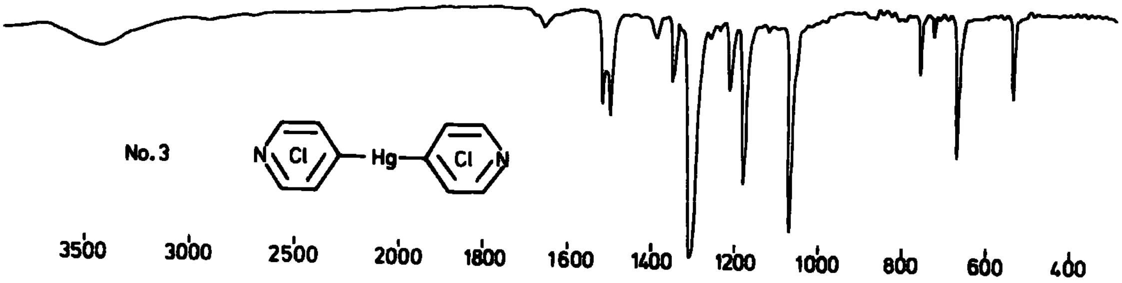
1.	Octafluoro-4,4'-bipyridyl (56).	KBr disc.
2.	4-H-tetrafluoropyridine (61).	Contact film.
3.	Bistetrachloropyridyl mercury (64).	KBr disc.
4.	Octachloro-4,4'-bipyridyl (65).	KBr disc.
5.	4-H-tetrachloropyridine (63).	KBr disc.
6.	Heptachlorobipyridyl (66).	KBr disc.
7.	2-H-heptafluoropropane (87).	Gas.
8.	Pentafluoroethane (90).	Gas.
9.	Octafluoro-4,4'-dimethoxybiphenyl (113).	KBr disc.
10.	Hexafluoro-2,2'-dihydro-4,4'-dimethoxybiphenyl (114).	KBr disc.
11.	Perfluoro-2,5-di-isopropylpyrazine (147).	Contact film.
12.	Perfluoro-2-isopropylpyrazine (146).	Contact film.
13.	Perfluoro-4-s-butylpyrazine (150).	Contact film.
14.	Perfluoro-2,5-di-s-butylpyrazine (151).	Contact film.
15.	Perfluoro-2,6-di-s-butylpyrazine (153).	Contact film.
16.	Perfluoro-2-isopropyl-5-s-butylpyrazine (181).	Contact film.
17.	Perfluoro-2-isopropyl-6-s-butylpyrazine (182).	Contact film.
18.	Perfluoro-4,5-di-isopropylpyrimidine (172).	Contact film.
19.	Perfluoro-4,5-di-s-butylpyrimidine (183).	Contact film.
20.	Perfluoro-5-isopropyl-4-s-butylpyrimidine (184).	Contact film.
21.	Perfluoro-4-isopropyl-5-s-butylpyrimidine (185).	Contact film.
22.	Perfluoro-4-isopropyl-5-s-butylpyridazine (180).	Contact film.



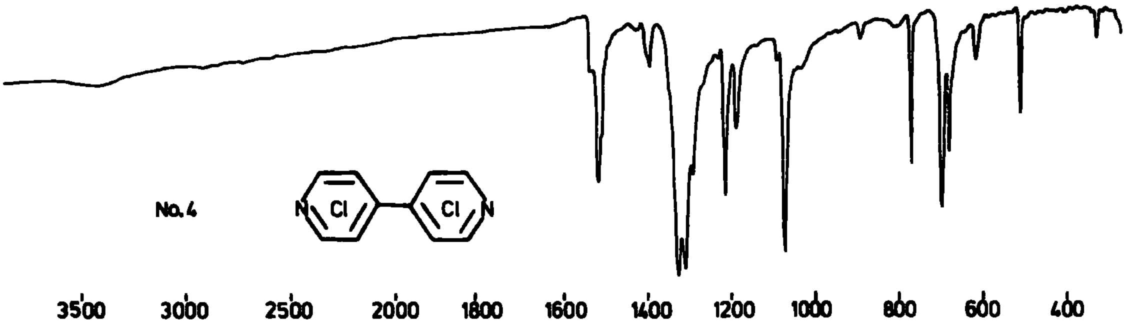
No. 1



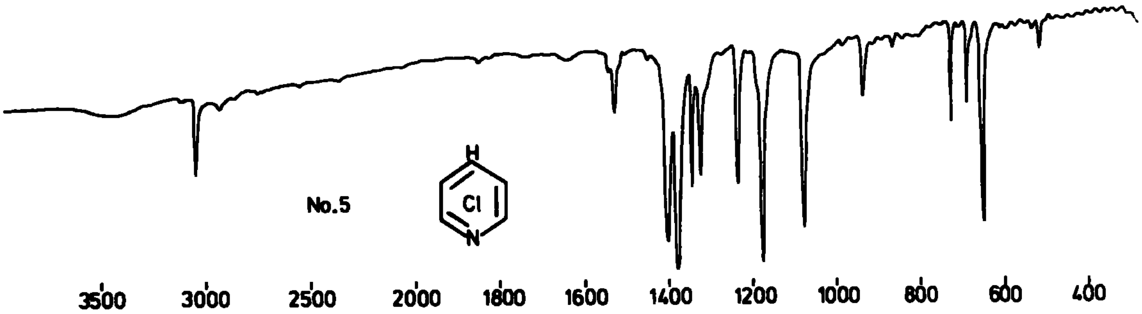
No. 2



No. 3

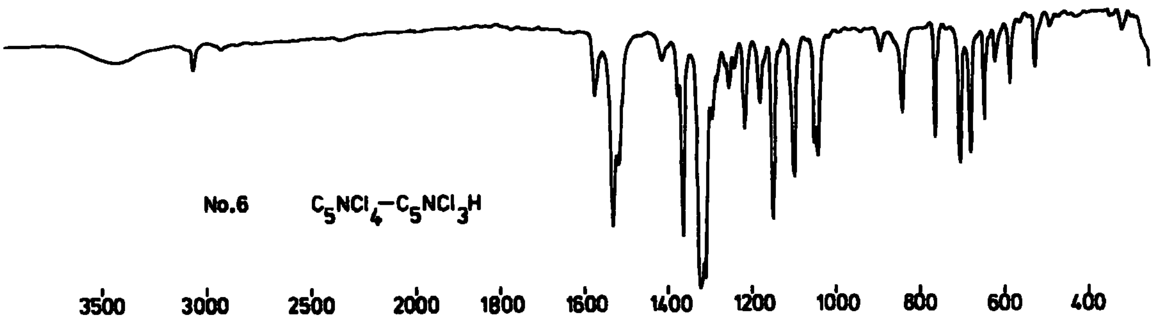


No. 4

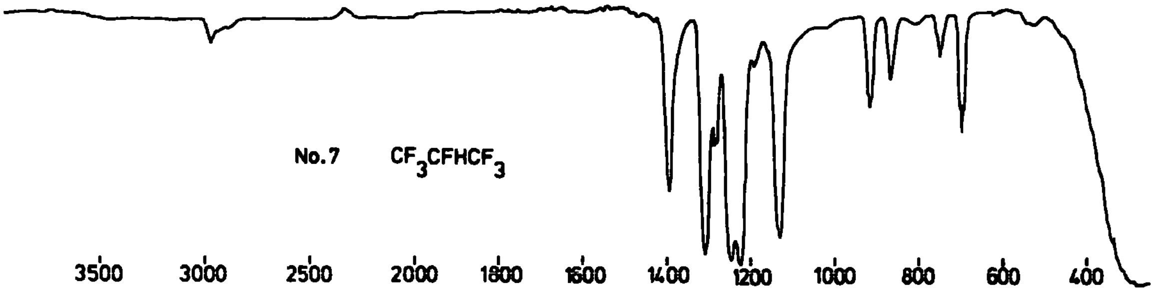


No. 5

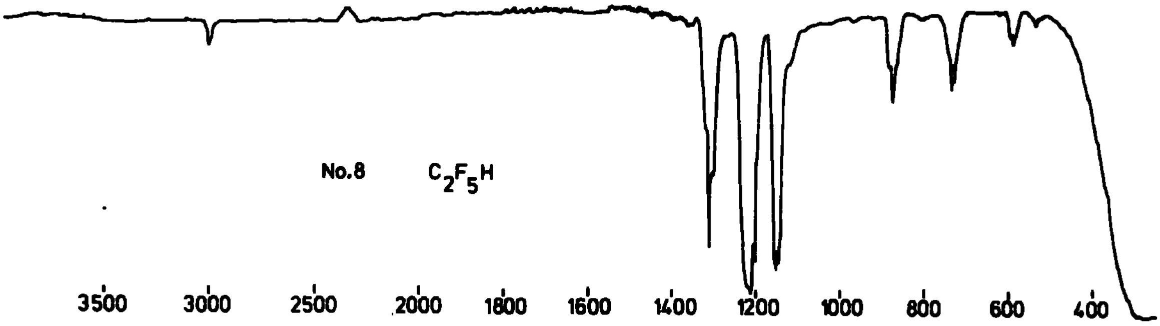
No.6 $C_5NCl_4{-}C_5NCl_3H$



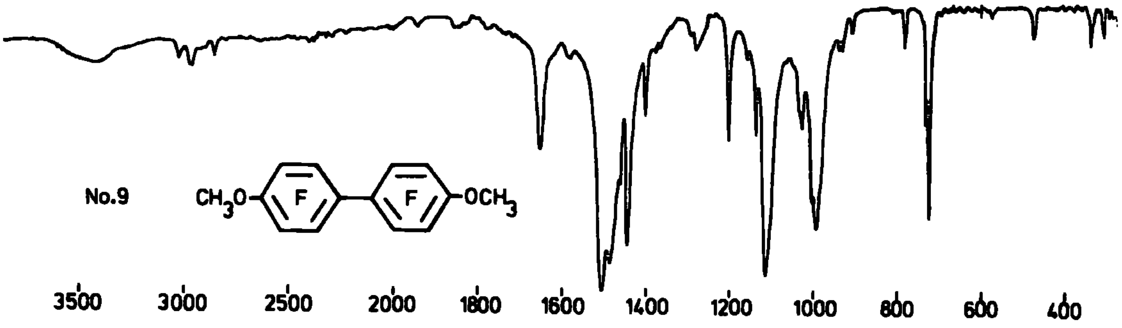
No.7 CF_3CFHCF_3



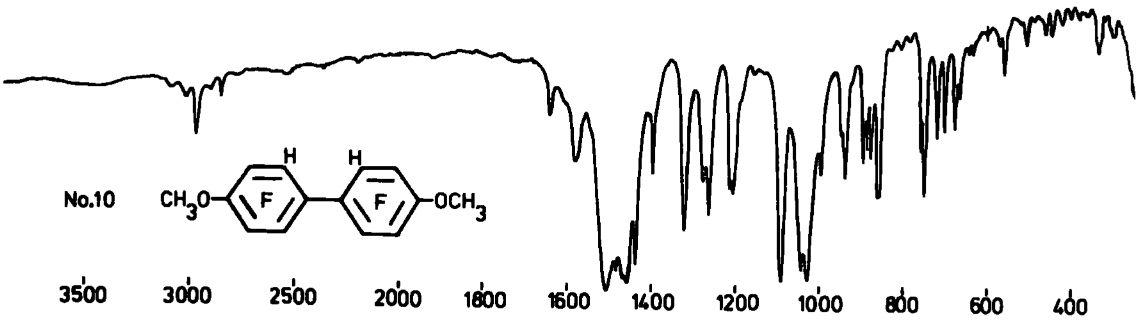
No.8 C_2F_5H

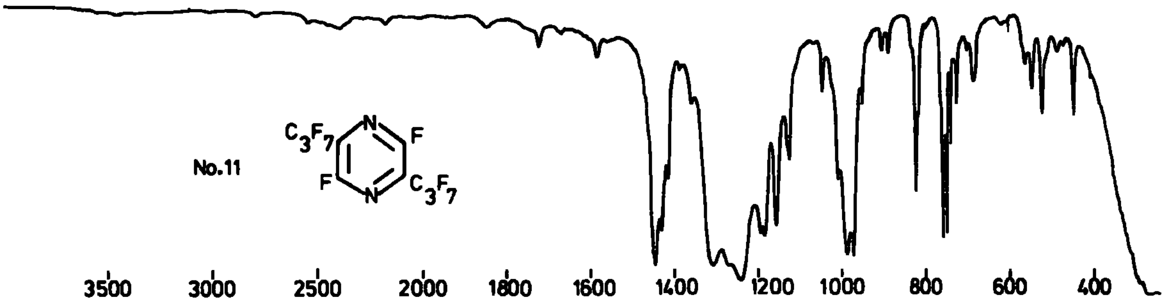


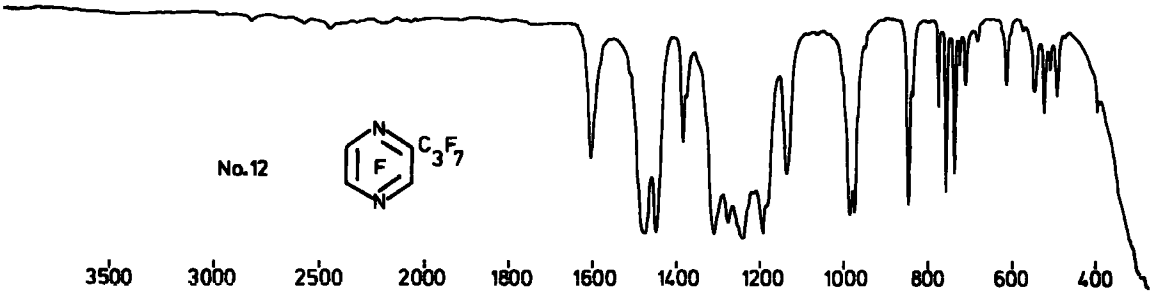
No.9

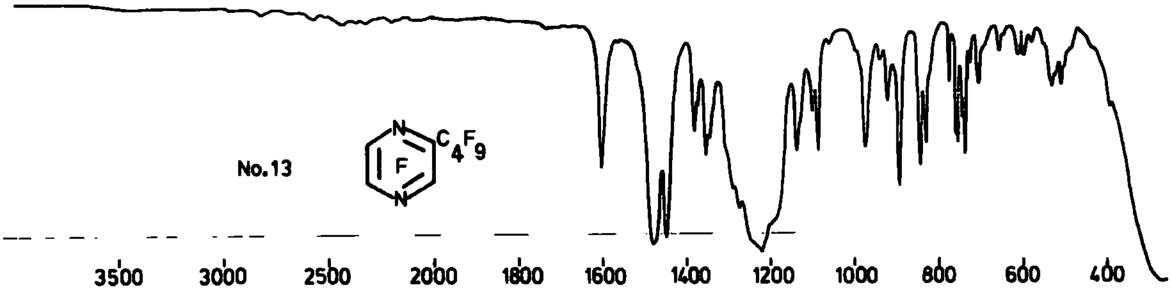


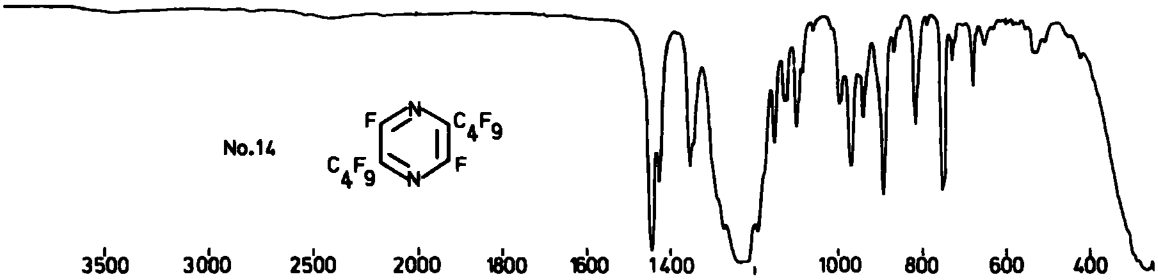
No.10

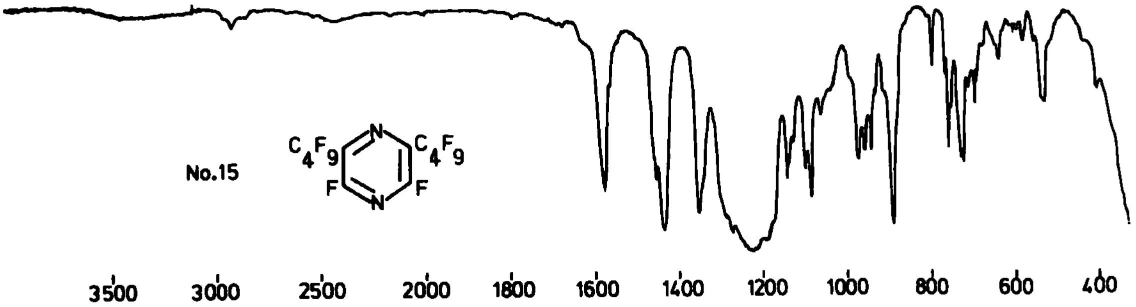


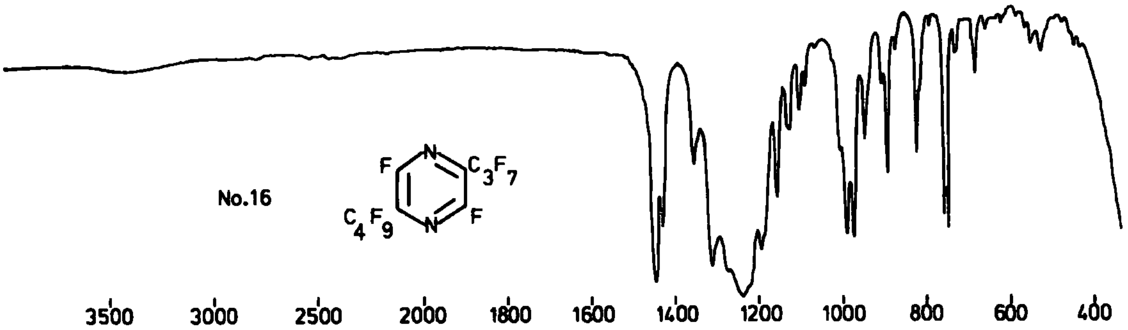

No.11

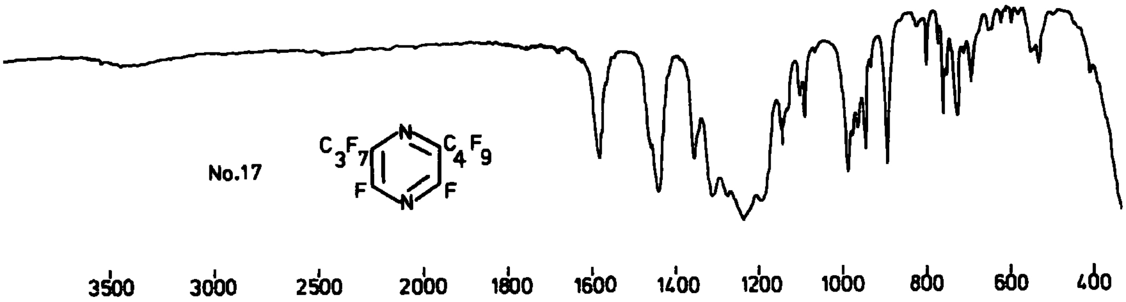

No.12

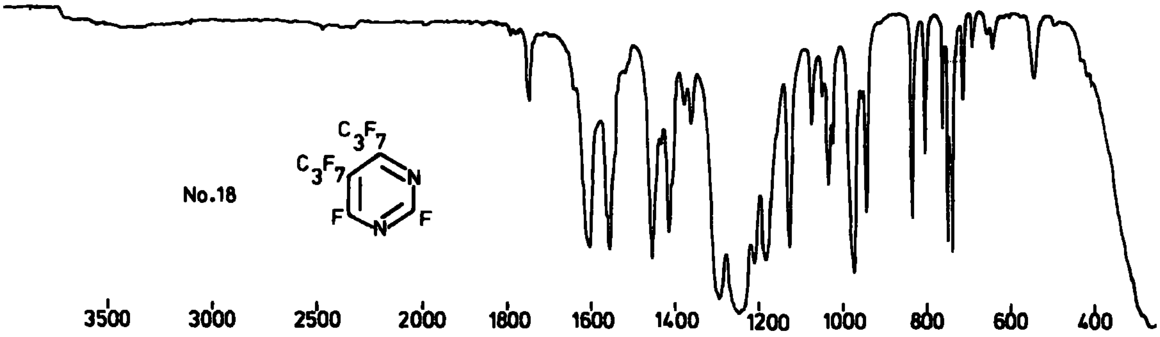

No.13

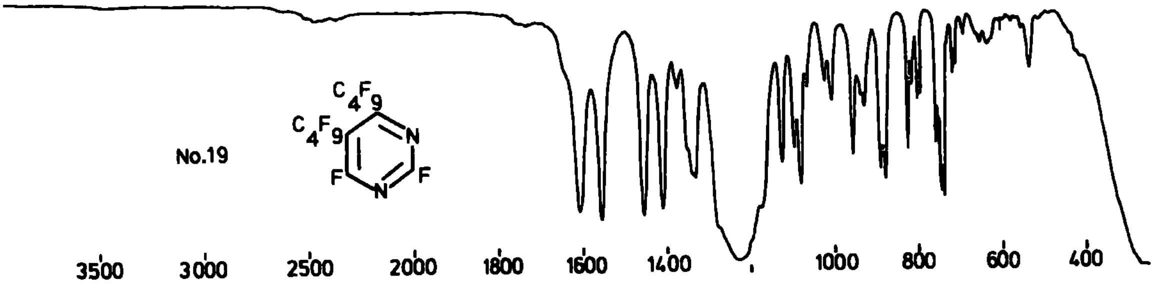

No.14

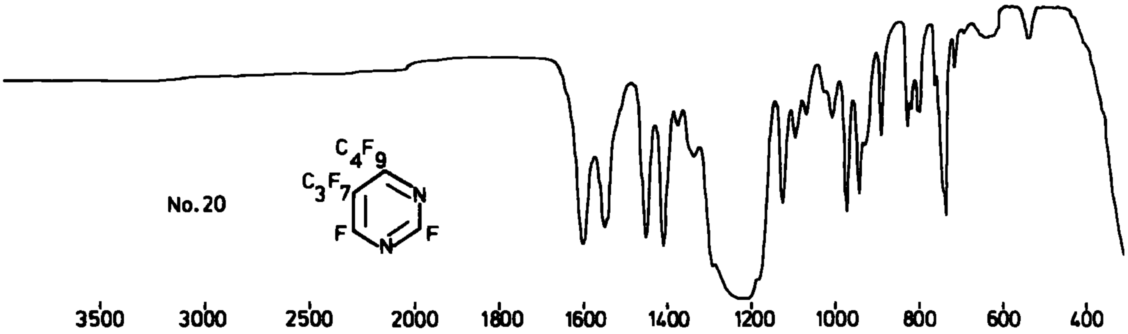

No.15

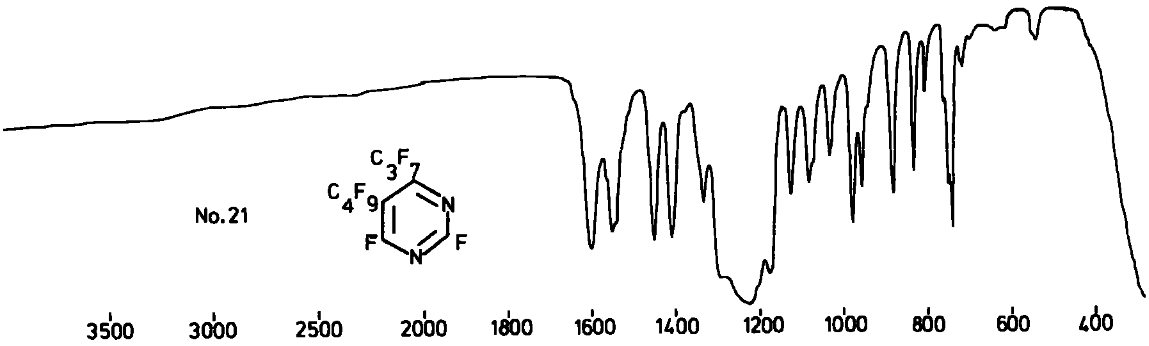

No.16


No.17


No.18

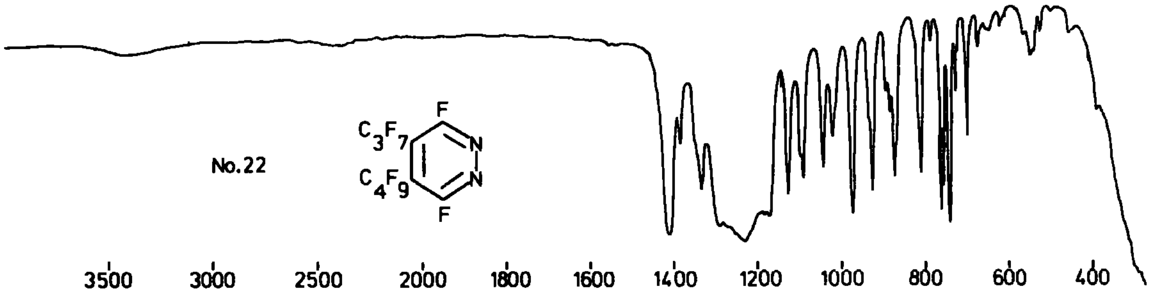

No.19


No.20



No.21

C_3F_7
C_4F_9
N
N
F
F
3500
3000
2500
2000
1800
1600
1400
1200
1000
800
600
400



No.22

F
C_3F_7
C_4F_9
N
N
F
3500
3000
2500
2000
1800
1600
1400
1200
1000
800
600
400

REFERENCES

1. M.M.Baizer, 'Organic Electrochemistry', Dekker, New York, 1973.
2. M.R.Rifi and F.H.Covitz, 'Introduction to Organic Electrochemistry', Dekker, New York, 1974.
3. N.L.Weinberg, 'Technique of Electroorganic Synthesis', Wiley-Interscience, New York, 1974.
4. L.Meites, in 'Physical Methods of Chemistry', Part II, editors A.Weisberger and B.W.Rossiter, Wiley-Interscience, New York, 1971.
5. L.E.Eberson and N.L.Weinberg, Chem. Eng. News, 1971, 49, 40.
6. A.Streitweiser, 'Molecular Orbital Theory for Organic Chemists', Wiley, New York, 1961.
7. G.J.Hoijtinck, Rec. Trav. Chim., 1958, 77, 555.
8. P.Delahey, 'New Instrumental Methods in Electrochemistry', Interscience, New York, 1954.
9. R.S.Nicholson and I.Shain, Anal. Chem., 1964, 36, 706.
10. R.S.Nicholson and I.Shain, Anal. Chem., 1965, 37, 178.
11. M.Mastragostini, L.Nadjo and J.M.Saveant, Electrochim. Acta., 1968, 13, 721.
12. For example: R.Annino, R.E.Erickson, J.Michalovic and B.McKay, J. Amer. Chem. Soc., 1966, 88, 4424.
13. G.Klopman, Helv. Chim. Acta, 1961, 44, 1908.
14. L.B.Rogers and A.J.Diefenderfer, J. Electrochem. Soc., 1967, 114, 942.
15. S.Wawzonek, R.C.Duty and J.H.Wagenknecht, J. Electrochem. Soc., 1964, 111, 74.
16. F.L.Lambert and K.Kobayashi, J. Amer. Chem. Soc., 1960, 82, 5324.

17. P.J.Elving and B.Pullman, Adv. Chem. Phys., 1961, 3, 1.

18. K.Fukui, K.Morokuma, H.Kato and Y.Yonezawa, Bull. Chem. Soc. Japan, 1963, 36, 217; Chem. Abstr., 1963, 59, 3540c.

19. M.R.Rifi, 'Reduction of Organic Halides', in Ref.1, p.279.

20. L.L.Miller and E.Riekena, J. Org. Chem., 1969, 34, 3359.

21. P.J.Elving, I.Rosenthall, J.R.Hayes and A.J.Martin, Anal. Chem., 1961, 33, 330.

22. F.A.Beland, S.O.Farwell, P.R.Callis and R.D.Geer, J. Electroanal. Chem. Interfacial Electrochem., 1977, 78, 145.

23. K.Alwair and J.Grimshaw, J. Chem. Soc., Perkin Trans.2, 1973, 1150.

24. K.Alwair and J.Grimshaw, J. Chem. Soc., Perkin Trans.2, 1973, 1811.

25. J.Grimshaw and J.Trocha-Grimshaw, J. Chem. Soc., Perkin Trans.2, 1974, 1383.

26. J.W.Sease, F.G.Burton and S.L.Nickol, J. Amer. Chem. Soc., 1968, 90, 2595.

27. M.R.Asirvatham and M.D.Hawley, J. Amer. Chem. Soc., 1975, 97, 5024.

28. M.v.Stackelburg and W.Stracke, Z. Elektrochem., 1949, 53, 118; Chem. Abstr., 1949, 43, 8916f.

29. J.Casanova and H.R.Rogers, J. Org. Chem., 1974, 39, 2408.

30. I.G.Markova and L.G.Feoktistov, Zh. Obshch. Khim., 1970, 40, 740; Chem. Abstr., 1970, 73, 41220x.

31. S.Wawzonek and J.H.Wagenknecht, J. Electrochem. Soc., 1963, 110, 420.

32. M.R.Rifi, J. Amer. Chem. Soc., 1967, 89, 4442.

33. F.H.Covitz, J. Amer. Chem. Soc., 1967, 89, 5403.

34. E.L.Colichman and S.K.Liu, J. Amer. Chem. Soc., 1954, 76, 913.

35. P.Iversen, J. Chem. Educ., 1971, 48, 136.

36. A.Inesi and L.Rampazzo, J. Electroanal. Chem. Interfacial Electrochem., 1973, 44, 25.

37. A.Inesi and L.Rampazzo, J. Electroanal. Chem. Interfacial Electrochem., 1974, 49, 85.

38. A.Inesi, L.Rampazzo and A.Zeppa, J. Electroanal. Chem. Interfacial Electrochem.,1976, 69, 203.

39. J.N.Seiber,(Dow Chem. Co.), U.S.Patent 3,687,827 ; Chem. Abstr., 1972, 77, 151980k.

40. J.P.Coleman, Naser-ud-din, H.G.Gilde, J.H.P.Utley, B.C.L.Weedon and L.Eberson, J. Chem. Soc., Perkin Trans.2, 1973, 1903.

41. P.Calais, P.Moreau and A.Commeyras, J. Electroanal. Chem. Interfacial Electrochem., 1977, 78, 271.

42. S.Wawzonek and R.C.Duty, J. Electrochem. Soc., 1961, 108, 1135.

43. N.S.Stepanova, M.M.Gol'din and L.G.Feoktistov, Elektrokhimiya, 1976, 12, 1166 ; Chem. Abstr., 1976, 85, 132633y.

44. K.M.Smirnov and A.P.Tomilov, Elektrokhimiya, 1975, 11, 784 ; Chem. Abstr., 1975, 83, 138931z.

45. K.M.Smirnov, A.P.Tomilov, L.G.Feoktistov and M.M.Gol'din, Zh. Prikl. Khim., (Leningrad), 1978, 51, 701 ; Chem. Abstr., 1978, 88, 160661m.

46. S.I.Zhdanov, Izv. Akad. Nauk S.S.S.R.,Ser. Khim., 1964, 6, 966 ; Chem. Abstr., 1965, 62, 234g.

47. A.M.Doyle, A.E.Pedler and J.C.Tatlow, J. Chem. Soc. (C), 1968, 2740.

48. A.E.Pedler and A.M.Doyle, J. Chem. Soc. (C), 1971, 282.

49. W.W.Bartle and B.R.Eggins, J. Polarogr. Soc., 1966, 12, 89.

50. V.P.Petrov, Izv. Sib. Otd. Akad. Nauk S.S.S.R., Ser. Khim. Nauk, 1966, 74 ; Chem. Abstr., 1967, 67, 17163m.

51. B.H.Campbell, Anal. Chem., 1972, 44, 1659.

52. J.C.Tatlow, Endeavour, 1963, 22, 89.

53. J.Burdon, Tetrahedron, 1965, 21, 3373.

54. S.O.Farwell, F.A.Beland and R.D.Geer, J. Electroanal. Chem. Interfacial Electrochem., 1975, **61**, 303.

55. S.O.Farwell, F.A.Beland and R.D.Geer, J. Electroanal. Chem. Interfacial Electrochem., 1975, **61**, 315.

56. D.T.Clark, personal communication.

57. F.G.Drakesmith, J. Chem. Soc., Perkin Trans.1, 1972, 89.

58. H.Nohe and H.Suter, Ger. Patent, 2,158,200 ; Chem. Abstr., 1973, **79**, 42045e.

59. J.Volke, O.Manousek and T.V.Troyepolskaya, J. Electroanal. Chem. Interfacial Electrochem., 1977, **85**, 163.

60. N.N.Ovsyannikov, V.N.Alekseev, A.N.Kashin, L.L.Knots, G.A.Tedoradze and A.B.Ershler, Elektrokhimiya, 1972, **8**, 1543 ; Chem. Abstr., 1973, **78**, 37151m.

61. L.L.Miller and A.K.Hoffmann, J. Amer. Chem. Soc., 1967, **89**, 593.

62. J.T.Keating and P.S.Skell, J. Org. Chem., 1969, **34**, 1479.

63. A.Laurent, E.Laurent and R.Tardivel, Tetrahedron, 1974, **30**, 3423.

64. A.Laurent, E.Laurent and R.Tardivel, Tetrahedron, 1974, **30**, 3431.

65. C.J.Brookes, P.L.Coe, D.M.Owen, A.E.Pedler and J.C.Tatlow, J. Chem. Soc., Chem. Commun., 1974, 323.

66. H.Millauer, Ger. Patent, 2,460,468 ; Chem. Abstr., 1976, **85**, 177239r.

67. H.Wendt, Ger. Patent, 2,100,381 ; Chem. Abstr., 1972, **77**, 114030e.

68. C.Parkanyi and R.Zahradnik, Collection Czech. Chem. Commun., 1965, **30**, 4287 ; Chem. Abstr., 1966, **64**, 7932c.

69. J.P.Coleman, M.Fleischmann and D.Pletcher, Electrochim. Acta, 1973, **18**, 331.

70. A.G.Hudson, A.E.Pedler and J.C.Tatlow, Tetrahedron, 1970, **26**, 3791.

71. C.M.Jenkins, A.E.Pedler and J.C.Tatlow, Tetrahedron, 1971, **27**, 2557.

72. R.F.Evilia and A.J.Diefenderfer, J. Electroanal. Chem. Interfacial Electrochem., 1969, 22, 407.

73. V.D.Parker, (Dow Chem. Co.), U.S. Patent, 3,694,332 ; Chem. Abstr., 1972, 77, 164492c.

74. D.M.W. van den Ham, G.F.S.Harrison, A.Spaans and D. van der Meer, Recl. Trav. Chim. Pays-Bas, 1975, 94, 168.

75. R.D.Chambers, J.Hutchinson and W.K.R.Musgrave, J. Chem. Soc., 1965, 5040.

76. R.D.Chambers, 'Fluorine in Organic Chemistry', Wiley-Interscience, New York, 1973 ; and references therein.

77. R.D.Chambers, F.G.Drakesmith and W.K.R.Musgrave, J. Chem. Soc., 1965, 5045.

78. D.A.Tyssee and M.M.Baizer, J. Org. Chem., 1974, 39, 2819.

79. J.W.Emsley, D.S.Stephenson, J.C.Lindon, L.Lunazzi and S.Pulga, J. Chem. Soc., Perkin Trans. II, 1975, 1541.

80. R.M.Silverstein, G.C.Bassler and T.C.Morrill, 'Spectrometric Identification of Organic Compounds', 3rd Edn., Wiley, New York, 1974.

81. J.D.Cook and B.J.Wakefield, J. Organomet. Chem., 1968, 13, 15.

82. C.K.Mann, J.L.Webb and H.M.Walborky, Tetrahedron Letters, 1966, (20), 2249.

83. H.J. den Hertog, J.C.M.Schogt, J. de Bruyn and A. de Klerk, Recl. Trav. Chim. Pays-Bas, 1950, 69, 673.

84. J.D.Cook, N.J.Foulger and B.J.Wakefield, J. Chem. Soc., Perkin Trans. I, 1972, 995.

85. H.Suschitzky, 'Polychloroaromatic Compounds', Plenum Press, London, 1974 ; and references therein.

86. J.J.R.Reed, Anal. Chem., 1967, 39, 1586.

87. A.Proctor, M.Sc. Dissertation, University of Newcastle, 1976.

88. W.Brunskill, W.T.Flowers, R.Gregory and R.N.Haszeldine, J. Chem. Soc. D, 1970, 1444.

89. P.D.Philpot, Ph.D. Thesis, Durham, 1975.

90. R.D.Chambers, A.A.Lindley, P.D.Philpot, H.C.Fielding and J.Hutchinson, Israel J. Chem., 1978, **17**, 150.

91. A.A.Lindley, Ph.D. Thesis, Durham, 1978.

92. D.P.Graham, J. Org. Chem., 1966, **31**, 955.

93. H.C.Fielding and A.J.Rudge, British Patent, 1,082,127, 1967.

94. S.Andreades, J. Amer. Chem. Soc., 1964, **86**, 2003.

95. A.P.I. Catalogue of Selected Infra-red Spectral Data, No. 1308.

96. A.C.Knipe, J. Chem. Ed., 1976, **53**, 619.

97. A.Ronlan, K.Bechgaard and V.D.Parker, Acta Chem. Scand., 1973, **27**, 2375 ; and references therein.

98. R.N.Adams, Acc. Chem. Res., 1969, **2**, 175.

99. V.D.Parker, Chem. Commun., 1969, 610.

100. A.Ronlan, O. Hammerlich and V.D.Parker, J. Amer. Chem. Soc., 1973, **95**, 7132.

101. K.Nyberg, Acta Chem. Scand., 1971, **25**, 2499.

102. L.Eberson and K.Nyberg, Adv. Phys. Org. Chem., 1976, **12**, 1.

103. F.H.Covitz, French Patent, 1,544,350 ; Chem. Abstr., 1970, **73**, 115824w.

104. Reference 2, p.278.

105. V.D.Parker and A.Ronlan, J. Amer. Chem. Soc., 1975, **97**, 4714.

106. F.Fichter and H.Ris, Helv. Chim. Acta, 1924, **7**, 803.

107. L.Eberson and B.Olofsson, Acta Chem. Scand., 1969, **23**, 2355.

108. K.Koyama, T.Susuki and S.Tsutsumi, Tetrahedron, 1967, **23**, 2665.

109. K.Nyberg, Chem. Commun., 1969, 774.

110. Y.-H.So, J.Y.Becher and L.L.Miller, J. Chem. Soc. Chem. Comm., 1975, 262.

111. L.Eberson, J. Amer. Chem. Soc., 1967, 89, 4669.

112. C.L.Perrin, Progr. Phys. Org. Chem.,1965, 3, 220.

113. L.Eberson and K.Nyberg, Tetrahedron R., 1976, 32, 2185.

114. K.Nyberg and L.-G.Wistrand, J. Chem. Soc. Chem. Comm., 1976, 898.

115. R.D.Chambers and D.J.Spring, Tetrahedron, 1971, 27, 669.

116. A.Ronlan, J.P.Coleman, O.Hammerlich and V.D.Parker, J. Amer. Chem. Soc., 1974, 96, 845.

117. N.Boden, J.W.Emsley, J.Feeney and L.H.Sutcliffe, Mol. Phys., 1964, 8, 467.

118. M.Hudlicky and H.M.Bell, J. Fluorine Chem., 1975, 6, 201.

119. R.E.Banks, F.Cuthbertson and W.K.R.Musgrave, Anal. Chim. Acta, 1955, 13, 442.

120. R.D.Chambers, J.Hutchinson and W.K.R.Musgrave, J. Chem. Soc., 1964, 3573.

121. W.H.Taplin, (Dow Chem. Co.), U.S.Patent, 3,420,833 ; Chem. Abstr., 1969, 71, 3279z.

122. E.E.Lewis and M.A.Naylor, J. Amer. Chem. Soc., 1947, 69, 1968.

123. E.J.Forbes, R.D.Richardson, M.Stacey and J.C.Tatlow, J. Chem. Soc., 1959, 2019.

124. R.Stephens and J.C.Tatlow, Chem. and Ind., 1957, 821.

125. J.Burdon and W.B.Hollyhead, J. Chem. Soc., 1965, 6326.

126. G.G.Yakobson, V.D.Shteingarts, A.I.Miroshnikov and N.N.Vorozhtsov, Dokl. Akad. Nauk SSSR, 1964, 159, 1109 ; Chem. Abstr., 1965, 62, 9040d.

127. D.Bryce-Smith and A.Gilbert, Tetrahedron, 1976, 32, 1309.

128. M.G.Barlow, R.N.Haszeldine and R.Hubbard, Chem. Commun., 1969, 202.

129. M.G.Barlow, R.N.Haszeldine and R.Hubbard, J. Chem. Soc. (C), 1970, 1232.

130. D.M.Lemal, J.V.Staros and V.Austel, J. Amer. Chem. Soc., 1969, 91, 3374

131. E.D.Clifton, W.T.Flowers and R.N.Haszeldine, Chem. Commun., 1969, 1216.

132. M.G.Barlow, R.N.Haszeldine and M.J.Kershaw, J. Chem. Soc., Perkin Trans.I, 1974, 1736.

133. R.D.Chambers and R.Middleton, J. Chem. Soc., Perkin Trans.I, 1977, 1500.

134. R.D.Chambers, J.A.H.MacBride, J.R.Maslakiewicz and K.C.Srivastava, J. Chem. Soc., Perkin Trans.I, 1975, 396.

135. L.Kaplan, K.E.Wilzbach, N.G.Brown and S.S.Yang, J. Amer. Chem. Soc., 1965, 87, 675.

136. S.Caplain and A.Lablache-Combier, Chem. Commun., 1970, 1247.

137. R.D.Chambers, J.R.Maslakiewicz and K.C.Srivastava, J. Chem. Soc., Perkin Trans.I, 1975, 1130.

138. M.G.Barlow, R.N.Haszeldine and J.A.Pickett, J. Chem Soc., Perkin Trans.I, 1978, 378.

139. R.D.Chambers, M.Clark, J.A.H.MacBride, W.K.R.Musgrave and K.C. Srivastava, J. Chem. Soc., Perkin Trans.I, 1974, 125.

140. C.G.Allison, R.D.Chambers, Yu.A.Cheburkov, J.A.H.MacBride and W.K.R.Musgrave, Chem. Commun., 1969, 1200.

141. R.D.Chambers, M.Clark, J.R.Maslakiewicz, W.K.R.Musgrave and P.G.Urben, J. Chem. Soc., Perkin Trans.I, 1974, 1513.

142. W.Mahler and T.Fukanaga, J. Chem. Soc. Chem. Comm., 1977, 307.

143. 'Handbook of Chemistry and Physics', Chemical Rubber Co., Cleveland, Ohio, 46th Edn., 1965, D 120.

144. R.D.Chambers, R.P.Corbally, T.F.Holmes and W.K.R.Musgrave, J. Chem. Soc., Perkin Trans.I, 1974, 108.

145. R.D.Chambers, J.A.Jackson, W.K.R.Musgrave, L.H.Sutcliffe and G.J.T.Tiddy, Tetrahedron, 1970, 26, 71.

146. R.D.Chambers, J.A.Jackson, S.Partington, P.D.Philpot and A.C.Young, J. Fluorine Chem.,1975, 6, 5.

147. R.D.Chambers, J.A.H.MacBride and W.K.R.Musgrave, J. Chem. Soc. (C), 1968, 2116.

148. R.D.Chambers, Yu.A.Cheburkov, J.A.H.MacBride and W.K.R.Musgrave, J. Chem. Soc. (C),1971, 532.

149. J.R.Maslakiewisz, Ph.D. Thesis, Durham, 1974.

150. D.W.Johnson, V.Austel, R.S.Field and D.M.Lemal, J. Amer. Chem. Soc. 1970, 92, 7505.

151. R.D.Chambers, J.A.H.MacBride and W.K.R.Musgrave, J. Chem. Soc. (C), 1971, 3384.

APPENDIX III

The Board of Studies in Chemistry requires that each postgraduate research thesis contain an appendix listing

(a) all research colloquia, research seminars and lectures (by external speakers) arranged by the Department of Chemistry since 1 October 1976:

and (b) all research conferences attended and papers read out by the writer of the thesis, during the period when the research for the thesis was carried out.

Research Colloquia, Seminars and Lectures

1 1976-77

a) University of Durham Chemistry Colloquia

Wednesday, 20th October

* Professor J.B. Hyne (University of Calgary), "New Research on an Old Element - Sulphur".

Wednesday, 10th November

* Dr. J.S. Ogden (Southampton University), "The Characterization of High Temperature Species by Matrix Isolation".

Wednesday, 17th November

* Dr. B.E.F. Fender (University of Oxford), "Familiar but Remarkable Inorganic Solids".

Wednesday, 24th November

Dr. M.I. Page (Huddersfield Polytechnic), "Large and Small Rate Enhancements of Intramolecular Catalysed Reactions".

Wednesday, 8th December

* Professor A.J. Leadbetter (University of Exeter), "Liquid Crystals".

Wednesday, 26th January

* Dr. A. Davis (ERDR), "The Weathering of Polymeric Materials".

Wednesday, 2nd February

Dr. M. Falk, (NRC Canada), "Structural Deductions from the Vibrational Spectrum of Water in Condensed Phases".

Wednesday, 9th February

* Professor R.O.C. Norman (U. of York), "Radical Cations; Intermediates in Organic Reactions.

Wednesday, 23rd February

Dr. G. Harris (U. of St. Andrews), "Halogen Adducts of Phosphines and Arsines".

Friday, 25th February

Professor H.T. Dieck (Frankfurt U.), "Diazadienes - New Powerful Low-Valent Metal Ligands".

Wednesday, 2nd March

* Dr. F. Hibbert (Birkbeck College, London), "Fast Reaction Studies of Slow Proton Transfers Involving Nitrogen and Oxygen Acids".

Friday, 4th March

* Dr. G. Brink (Rhodes U., R.S.A.), "Dielectric Studies of Hydrogen Bonding in Alcohols".

Wednesday, 9th March

* Dr. I.O. Sutherland (Sheffield U.), "The Stevens' Rearrangement: Orbital Symmetry and Radical Pairs".

Friday, 18th March

* Professor Hans Bock (Frankfurt U.), "Photoelectron Spectra and Molecular Properties: A Vademecum for the Chemist".

Wednesday, 30th March

* Dr. J.R. MacCallum (U. of St. Andrews), "Photooxidation of Polymers".

Wednesday 20th April

* Dr. D.M.J. Lilley (G.D. Searle, Research Div.), "Tails of Chromatin-Structure - Progress towards a Working Model".

Wednesday, 27th April

* Dr. M.P. Stevens (Univ. of Hartford), "Photocycloaddition Polymerisation".

Wednesday, 4th May

Dr. G.C. Tabisz (Univ. of Manitoba), "Collision Induced Light Scattering by Compressed Molecular Gases".

Wednesday, 11th May

* Dr. R.E. Banks (UMIST), "The Reaction of Hexafluoropropene with Heterocyclic N-Oxides".

Wednesday, 18th May

Dr. J. Atwood (Univ. of Alabama), "Novel Solution Behaviour of Anionic Organoaluminium Compounds: the Formation of Liquid Clathrates".

Wednesday, 25th May

Professor M.M. Kreevoy (Univ. of Minnesota), "The Dynamics of Proton Transfer in Solution".

Wednesday, 1st June

Dr. J. McCleverty (Univ. of Sheffield), "Consequences of Deprivation and Overcrowding on the Chemistry of Molybdenum and Tungsten".

Wednesday, 6th July

Professor J. Passmore (Univ. of Brunswick), "Adducts Between Group V Pentahalides and a Postscript on S_7I^+".

b) Durham University Chemical Society

Tuesday, 19th October

* Dr. J.A. Salthouse (Univ. of Manchester), "Chemistry and Energy".

Tuesday, 26th October

* Dr. R.E. Richards (Univ. of Oxford), "NMR Measurements on Intact Biological Tissue".

Tuesday, 2nd November

* Dr. B. Sutcliffe (Univ. of York), "The Chemical Bond as a Figment of the Imagination".

Tuesday, 16th November

* Mr. R. Ficken (Rohm & Haas), "The Graduate in Industry".

Tuesday, 30th November

* Dr. R.J. Donovan (Univ. of Edinburgh), "The Chemistry of the Atmosphere".

Tuesday, 18th January

* Professor I. Fells (Univ. of Newcastle), "Energy Storage: the Chemists' Contribution to the Problem".

Tuesday, 8th February

Dr. M.J. Cleare (Johnson Matthey Research Centre), "Platinum Group Metal Compounds as Anti-Cancer Agents".

Tuesday, 1st March

Professor J.A.S. Smith (Q.E. College, London), "Double Resonance".

Tuesday, 8th March

* Professor C. Eaborn (Univ. of Sussex), "Structure and Reactivity".

2 1977-78

a) University of Durham Chemistry Colloquia

Tuesday, 27th September

* Dr. T.J. Broxton (La Trobe Univ. Australia), "Interaction of Aryldiazonium Salts and Arylazoalkyl Ethers in Basic Alcoholic Solvents".

Wednesday, 19th October

* Dr. B. Heyn (Univ. of Jena, D.D.R.), "σ-Organo-Molybdenum Complexes as Alkene Polymerisation Catalysts".

Thursday, 27th October

* Professor R.A. Filler (Illinois Inst. of Technology, U.S.A.), "Reactions of Organic Compounds with Xenon Fluorides".

Wednesday, 2nd November

Dr. N. Boden (Univ. of Leeds), "NMR Spin-Echo Experiments for Studying Structure and Dynamical Properties of Materials Containing Interacting Spin-½ Pairs".

Wednesday, 9th November

* Dr. A.R. Butler (Univ. of St. Andrews), "Why I lost Faith in Linear Free Energy Relationships".

Wednesday, 7th December

Dr. P.A. Madden (Univ. of Cambridge), "Raman Studies of Molecular Motions in Liquids".

Wednesday, 14th December

Dr. R.O. Gould (Univ. of Edinburgh), "Crystallography to the Rescue in Ruthenium Chemistry".

Wednesday, 25th January

* Dr. G. Richards, (Univ. of Oxford), "Quantum Pharmacology".

Wednesday 1st February, 2.30 p.m.

* Professor K.J. Ivin (Queens University, Belfast), "The olefin metathesis reaction: mechanism of ring-opening polymerisation of cycloalkenes".

Friday 3rd February

* Dr A. Hartog (Free University, Amsterdam, Holland), "Surprising recent Studies in Organo-magnesium Chemistry".

Wednesday 22 February

* Professor J.D. Birchall (Mond Division, I.C.I. Ltd.), "Silicon in the Biosphere".

Wednesday 1st March

* Dr A. Williams (University of Kent), "Acyl Group Transfer Reactions".

Friday 3rd March

* Dr G. van Koten (University of Amsterdam, Holland), "Structure and Reactivity of Arylkopper Cluster Compounds".

Wednesday 15 March

Professor G. Scott (University of Aston), "Fashioning Plastics to match the Environment".

Wednesday 22 March

* Professor H. Vahrenkamp (University of Freiburg, Germany), "Metal-Metal Bonds in Organometallic Complexes".

Wednesday 19 April

Dr M. Barber (UMIST), "Secondary Ion Mass Spectra of Surfaces and Absorbed Species".

Tuesday 16th May

Dr P. Ferguson (C.N.R.S., Grenoble), "Surface Plasma Waves and Adsorbed Species on Metals".

Thursday 18th May

Professor M. Gordon (University of Essex), "Three Critical Points in Polymer Science".

Monday 22nd May

* Professor D. Tuck (University of Windsor, Ontario), "Electrochemical Synthesis of Inorganic and Organometallic Compounds".

Wednesday - Thursday 24th, 25th May

Professor P. von R. Schleyer (University of Erlangen, Nürnberg),

* I. "Planar Tetra-co-ordinate Methanes, Perpendicular Ethylenes, and Planar Allenes".

* II. "Aromaticity in Three Dimensions".

III. "Non-classical Carbocations".

Wednesday 21st June

Dr S.K. Tyrlik (Academy of Science, Warsaw), "Dimethylglyoxime-cobalt Complexes - Catalytic Black Boxes".

Friday 23rd June

Professor W.B. Pearson (University of Florida), "Diode Laser Spectroscopy at 16 μm".

Friday 30th June

* Professor G. Mateescu (Cape Western Reserve University), "A Concerted Spectroscopy Approach to the Characterization of Ions and Ion Pairs : Facts, Plans, and Dreams".

(b) Durham University Chemical Society

Thursday 13th October

* Dr J. C. Young, Mr A.J.S. Williams (University of Aberystwyth), "Experiments and Considerations Touching Colour".

Thursday 20th October

* Dr R.L. Williams (Metropolitan Police Forensic Science Dept.), "Science and Crime".

Thursday 3rd November

* Dr G.W. Gray (University of Hull), "Liquid Crystals - Their Origins and Applications".

Thursday 24th November

Mr G. Russell (Alcan), "Designing for Social Acceptability".

Thursday 1st December

Dr B.F.G. Johnson (University of Cambridge), "Chemistry of Binary Metal Carbonyls".

Thursday 2nd February

* Professor R.A. Raphael (University of Cambridge), "Bizarre Reactions of Acetylenic Compounds".

Thursday 16th February

* Professor G.W.A. Fowles (University of Reading), "Home Winemaking".

Thursday 2nd March

* Professor M.W. Roberts (University of Bradford), "The Discovery of Molecular Events at Solid Surfaces".

Thursday 9th March

* Professor H. Suschitzky (University of Salford), "Fruitful Fissions of Benzofuroxans".

Thursday 4th May

* Professor J. Chatt (University of Sussex), "Reactions of Co-ordinated Dinitrogen".

Tuesday 9th May

* Professor G.A. Olah (Case Western Reserve University, Cleveland, Ohio), "Electrophilic Reactions of Hydrocarbons".

3 1978-79

a) University of Durham Chemistry Colloquia

Friday, 8th September

* Dr. A. Diaz (I.B.M., San Jose, California),

"Chemical Behaviour of Electrode Surface Bonded Molecules".

Friday, 15th September

Professor W. Siebert (Marburg, West Germany),

"Boron Heterocycles as Ligands in Transition Metal Chemistry".

Friday, 22nd September

Professor T. Fehlner (Notre Dame, U.S.A.),

"Ferraboranes: Syntheses and Photochemistry".

b) Durham University Chemical Society

Tuesday, 10th October

* Professor H. C. Brown (Purdue University),

"The Tool of Increasing Electron Demand in the Study of Cationic Processes".

Thursday, 19th October

Mr. F.C. Shenton (Public Analyst, Co. Durham)

"There is Death in the Pot".

* An asterisk indicates events attended.