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Chapter 11

A GUIDE TO MODERN ORGANOFLUORINE CHEMISTRY[1]

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New vistas in organic chemistry

Promises

Fluorine forms the strongest known single bond to carbon,[2] and, as a substituent, exerts but modest spatial demands, especially when compared with the other halogens.[3] Only in the case of fluorine, therefore, can *complete* replacement of hydrogen by halogen be envisaged in *any* hydrocarbon or functionalised derivative thereof to produce a halogenocarbon analogue. A novel and completely man-made branch of organic chemistry — *fluorocarbon chemistry* — is thereby perceived, in which the fundamental tenets of the parent subject hold, yet exciting new vistas appear in terms of mechanism, synthetic methodology and commercial applications. Since stepwise conversion of hydrocarbon material to fluorocarbon is notionally allowed, *e.g.*

$$\begin{tikzcd}
CH_3CH_3 \arrow[d] & CH_2FCH_2F \arrow[r] & CH_2FCHF_2 \arrow[r] \arrow[dr] & CHF_2CHF_2 \arrow[dr] & \\
CH_3CH_2F \arrow[r] \arrow[ur] & CH_3CHF_2 \arrow[r] \arrow[ur] & CH_3CF_3 \arrow[r] & CH_2FCF_3 \arrow[r] & CHF_2CF_3 \arrow[d] \\
 & & & & CF_3CF_3
\end{tikzcd}$$

$$CH_3CO_2H \longrightarrow CH_2FCO_2H \longrightarrow CHF_2CO_2H \longrightarrow CF_3CO_2H$$

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[1] See Appendix 11.1, p. 285, for information on the nomenclature used here for fluorocarbons and their derivatives.

[2] The average dissociation energy of the C—F bond is 485 kJ mol^{-1} (116 kcal mol^{-1}) [*cf.* C—H, 413 (98.8); C—O, 358 (85.5); C—C, 346 (82.6); C—Cl, 339 (81); C—Br, 284.5 (68); C—I, 213 kJ mol^{-1} (51 kcal mol^{-1})].

[3] 'Recommended' values of van der Waals' radii (r_W) for volume calculations (see ref. 118) of bound halogen atoms in n-alkyl halides: F, 1.40; Cl, 1.73; Br, 1.84; I, 2.01 Å [*cf.* $r_W(C_{aliphatic})$ 1.70 Å; $r_W(H_{aliphatic})$ 1.20 Å].

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considerably more organofluorine compounds are theoretically capable of synthesis than there are organic substances known today; this further increases the probability of discovering materials of commercial value. Much is to be gained from an academic viewpoint too: since fluorine is the most electronegative element, traversal of structural continua between hydrocarbon compounds and their fluorocarbon analogues would be expected to result not only in gradual changes in physical properties and rates of reaction but also to encounters with cross-over points in the mechanisms of some processes. Clearly, fluorocarbon chemistry itself ought to prove not only a testing ground for mechanisms and principles currently accepted in the hydrocarbon field, but a source of new concepts and theories, and perhaps even novel structural types.

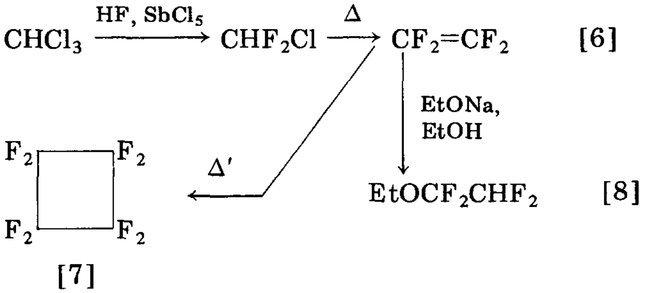
Incentives

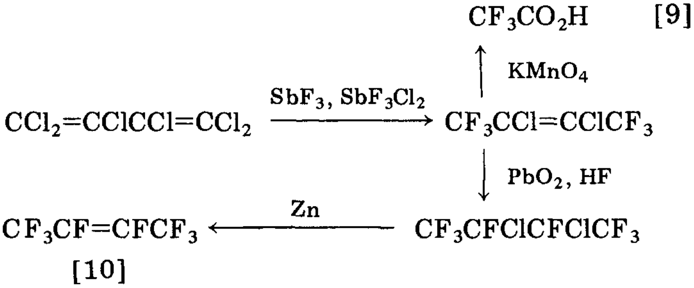
The above paragraph is an imaginary gambit for a 1940s application for research funding in the organofluorine area with some benefit of hindsight. It appears to reflect the thoughts of Joe Simons [1], and possibly of others, when the outcome of his work with Block on the direct fluorination of carbon was contemplated (see p. 91). Certainly the tremendous and unparalleled opportunities available to chemists in academia and industry were spelled out clearly by McBee [2] and Simons [1] in the much-read March 1947 issue of *Industrial and Engineering Chemistry* dealing with the Manhattan District development of fluorine chemistry. In the same issue [3], Grosse and Cady threw down a sizeable gauntlet to pundits in synthetic organic chemistry by pointing out that some 10^{12} fluoro-organic chemicals could be patterned structurally on the then known organic compounds; and McBee offered the incentive remark "Peacetime products containing fluorine are expected to include new and useful dyes, plastics, pharmaceuticals, lubricants, tanning agents, metal fluxes, fumigants, insecticides, fungicides, germicides, fire extinguishers, solvents, fireproofing compounds, heat transfer media, and other products of benefit to society" [2].

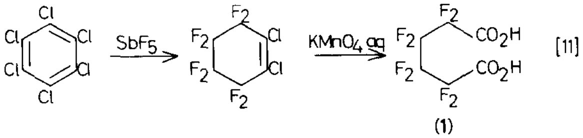
Simons' fluorocarbon aeroplane

Simons campaigned vigorously for the funding of a research and development thrust in the *fluorocarbon* area, where materials would differ maximally from their hydrocarbon counterparts and major commercial prizes could be foreseen to await discovery. For example [4], using arguments hinging on the outstanding chemical inertness and high thermal stability of saturated fluorocarbons, and taking into account their unique physical properties, he described an imaginary aeroplane in which fire hazards were minimised through the use of plastics, elastomers, paints, lubricants, hydraulic oils and turbine working fluids of the fluorocarbon class, *i.e.* materials in which the C—F bond content had been maximised consistent with the required service properties.

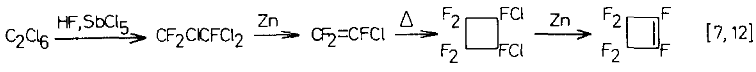
Progress along such lines was seen to demand expenditure of considerable effort to develop general methods of preparation for a host of fluorocarbon derivatives, *i.e.* compounds containing the familiar functional groups of 'normal' (hydrocarbon) organic and of organoelemental chemistry. Naturally, saturated fluorocarbons, being so unreactive, were not viewed as likely to play important roles as synthetic intermediates. By contrast, the utility of chlorofluorocarbons as precursors of fluorocarbon systems had already been firmly established [5] by building on the pioneering studies summarised in Chapter 4, *e.g.*







$$(1) \xrightarrow{EtOH/H^+} EtO_2C(CF_2)_4CO_2Et \xrightarrow[(ii)\,P_2O_5]{(i)\,NH_3} N{\equiv}C(CF_2)_4C{\equiv}N \xrightarrow{H_2/PtO_2} H_2NCH_2(CF_2)_4CH_2NH_2 \quad [11]$$



This entrée to the domain of fluorocarbon chemistry provided by Swarts–Henne methodology has been the major factor responsible for the development of the subject in both commercial and academic circles ever since. Also of immense importance to the development of fluorocarbon chemistry has been the commercialisation of an HF-based electrochemical fluorination method (ECF) invented by Simons during World War II but not advertised until 1949 (see p. 269).

By comparison with synthetic methods based ultimately on halogen exchange or ECF, those relying on elemental fluorine fall into a minority class. Nonetheless, important work has been done with fluorine itself, and with reagents made from it; hence usage of the element in organic chemistry has increased considerably during the past 15 years.

Current position

Writing in 1970 on fluorine compounds as teaching aids in organic theory, Young asserted that "By and large, an instructor can now substitute a perfluoro analog for a conventional organic compound with the assurance that he is talking about a real compound rather than a hypothetical one" [13]. Shortly afterwards (1974), the famous Russian fluorine chemist I. L. Knunyants (see Appendix 11.4) pointed out that since World War II organofluorine chemistry had grown into a new and exciting field, characterised by orderliness and systematisation, and, in many respects, was even then a richer field of knowledge than hydrocarbon chemistry [14]. Such statements testify to the great advances achieved by fluorocarbon chemists during the 1950s and 1960s, advances which in no small measure were made possible by the introduction of techniques now absolutely indispensable in this area of chemistry, namely gas chromatography[4] and ^{19}F nuclear magnetic resonance spectroscopy.[5] Routine, reliable methods of elemental analysis for fluorocarbons and their derivatives had been available for some time.[6]

During the past 15 years, the fluorocarbon field has become even more sophisticated, especially where synthesis is concerned, and of much wider international appeal. Joining the U.S.A., Great Britain and the U.S.S.R. — countries traditionally very active in fluorocarbon chemistry — have been France, Germany, Japan and Italy, whilst ever-increasing participation by Chinese groups is noticeable [251].

Interest in partially fluorinated organic compounds has also reached an all-time record, particularly through the continuing search for new

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[4] Analytical gas–liquid chromatography was adapted for preparative work in fluorocarbon chemistry by the authors [15] in the early 1950s, using home-made equipment. The first successful commercial gas chromatograph (Model 154) in the U.S.A. was introduced by the Perkin–Elmer Corporation in May 1955 [16].

[5] See Appendix 11.2 for a summary of the application of NMR spectroscopy to organofluorine chemistry. Infrared spectroscopic analysis of fluorocarbon-type compounds has also been of great value; for reviews see refs. 17 and 18; the former contains a set of actual spectra. Standard instrumentation and sampling methods are employed, gas sampling being popular owing to the high volatilities associated with perfluorinated materials. Ref. 19 is a review of mass spectrometric analysis of fluorinated compounds, another important source of structural information.

[6] See Appendix 11.3.

biologically-active molecules containing C—F bonds and recent developments in medical diagnostics.[7] Such work has created an enormous demand for reagents capable of effecting efficient introduction of a single fluorine substituent, or a CF_2 or CF_3 group, at specific sites in all manner of molecular structures.

Specific fluorinating agents

Not only have 'old' reagents (see Chapters 4 and 5) — including elemental fluorine — been scrutinised with a view to improvement, but over the years a range of completely new synthetic tools has been introduced for the construction of C—F bonds at specific molecular sites (see ref. 20 and Chapter 14). Of considerable and lasting importance was the addition of sulphur tetrafluoride [21] to the list of fluorinating agents in 1960 through research carried out by the powerful Du Pont fluorine team; its chief value is its ability to effect the functional group conversions $C{=}O \rightarrow CF_2$ and $CO_2H \rightarrow COF \rightarrow CF_3$. Sulphur tetrafluoride — a toxic gas — has been supplemented recently by its liquid derivative diethylaminosulphur trifluoride (DAST) [$Et_2NSiMe_3 + SF_4 \rightarrow Et_2NSF_3 + FSiMe_3$ (ref. 22)], a reagent[8] prized for its ability to replace hydroxyl and carbonyl oxygen by fluorine under mild conditions [23]. Treatment of sulphur tetrafluoride with an excess of a (dialkylamino)trimethylsilane provides access to so-called TAS reagents [26]. The most popular one at present, tris(dimethylamino)sulphonium difluorotrimethylsiliconate [$SF_4 + 3\ Me_2NSiMe_3 \rightarrow (Me_2N)_3S^+\ Me_3SiF_2^-$] [27], and the analogous bifluoride it yields on controlled hydrolysis [28] — known as TASF and $TASHF_2$, respectively — are the latest reagents not only in a long line of specific fluorinating agents (*e.g.* see Scheme 11.1) but of fluorine-containing reagents valuable in general organic synthesis [28, 30].[9]

Organofluorine reagents

Polar effects

Most fluorine-containing reagents of value to non-fluorine chemists fall into the *organo*fluorine class. Instances of synthetic, analytical, mechanistic

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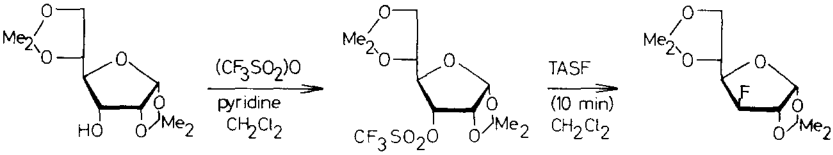
[7] See Chapter 13.

[8] With respect to explosive hazards associated with the synthesis and utilisation of DAST [24], Middleton [25] is of the opinion that no violent decompositions seem likely to occur when the reagent is handled in solution, or when the temperature of neat samples is kept below 50 °C — as during distillation at 10 mmHg pressure or below for isolation purposes (b.p. 46 - 47 °C at 10 mmHg pressure [22]).

[9] Notably as initiators (especially the bifluoride, $(Me_2N)_3S^+\ HF_2^-$) for use in Du Pont's novel GTP (group-transfer polymerisation) process for acrylic monomers developed recently [28]. For some examples of the use of $(Me_2N)_3S^+\ Me_3SiF_2^-$ or its tris(diethylamino) analogue in non-polymer synthesis, see ref. 30. Examples of preparative applications for several inorganic fluorine-containing reagents can be found in Chapter 14. For reviews of the use of fluoride ion in organic synthesis, see refs. 31 and 32.



Scheme 11.1. Rapid synthesis of a deoxyfluoro sugar using tris(dimethylamino)sulphonium difluorotrimethylsiliconate (TASF) and trifluoromethanesulphonic anhydride (triflic anhydride) [29]. This is a modern analogue of the very first synthesis of a C—F bond (in CH_3F) by Dumas and Péligot (1835; see p. 72).

and separative applications for compounds containing C—F bonds have in fact reached astronomical figures, mainly owing to the commercial availability of two fluorocarbon acids — CF_3CO_2H and CF_3SO_3H (pp. 252, 269). These compounds are much stronger proton donors than their hydrocarbon analogues because of the *polar effect* universally associated with a perfluoroalkyl group, namely powerful electron withdrawal via through-bond (σ-inductive effect, $-I_\sigma$) and through-space (field effect) mechanisms. Indeed trifluoromethanesulphonic acid, CF_3SO_3H (*triflic acid*), is classed as a Brønsted superacid[10] ($H_0 = -14$ [33]) and acclaimed as the strongest monoprotonic organic acid; accordingly, the trifluoromethanesulphonate (*triflate*, TfO^-) anion, $CF_3SO_2O^-$, is a super leaving group, its nucleofugality being about 10^4 - 10^5 times higher than that of the familiar *p*-toluenesulphonate entity (tosylate, TsO^-).[11] Graduate chemists nowadays cannot fail to have heard about applications of these fluorinated acids and derived compounds.

They will surely be aware also of the use of the classical Sanger reagent (2,4-dinitrofluorobenzene) for the determination of *N*-terminal amino-acid residues in peptide chains. This utilises the very ready replacement of fluorine from particular C—F bonds activated by the presence nearby in the molecule of powerful electron-attracting groups. Nucelophilic displacement of fluorine from aromatic carbon will be mentioned again later, but note that the order of halogen mobility usually observed for anionic attack on aryl systems is $F \gg Cl > Br > I$. The effect is utilised[12] in the manufacture of I.C.I.'s important new high-performance thermoplastic Victrex® PEEK [34], a 'polyetheretherketone' $\left[OArOArC(O)Ar \right]_n$ ($Ar = 1,4\text{-}C_6H_4$), which is derived from 4,4′-difluorobenzophenone, a monomer obtainable via large-scale application of Balz–Schiemann methodology, and hydroquinone.

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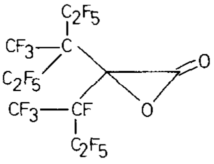
[10] A Brønsted acid is accorded superacid status if its acidity exceeds that of 100% sulphuric acid ($H_0 = -12$) [33].

[11] Note that the reactivity of the triflate leaving group is utilised in the synthesis shown in Scheme 11.1.

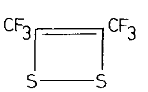
[12] Directly extending the pioneering work with aryl fluorides recorded in Chapter 4, this application even relates back to the 'mistake' in the very first paper on fluoroaromatic compounds (see p. 75), which has proved to be of much more lasting significance than the planned experiment!

The perfluoroalkyl effect

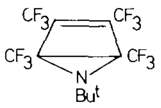
A more sophisticated example of the synthesis of a hydrocarbon polymer from a fluorinated starting material concerns the recent improved method of production of 'Durham poly(acetylene)' from cyclo-octatetraene and hexafluorobut-2-yne [35], a potent dienophile of the fluorocarbon class which yields a thermal 1,4-adduct even with benzene [36]. The method hinges on the remarkable tendency of perfluoroalkyl substituents to stabilise small-ring compounds — the so-called *perfluoroalkyl effect* [37],[13] a phenomenon which allows the bis(trifluoromethyl)pentacyclodecene **2** to be isolated (see Scheme 11.2). The striking thermal stability of perfluoroalkylated strained rings, which is thought to be a kinetic phenomenon [39], has enabled a number of compound types either unknown in hydrocarbon chemistry (*e.g.* **3** - **6**) or rarely isolable (*e.g.* **7**, **8**) to be obtained.[14]



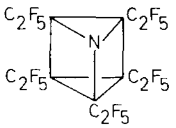
(3) [41]



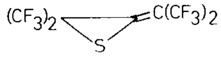
(4) [42]



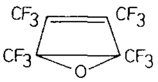
(5) [43]



(6) [44]



(7) [45]



(8) [46][15]

[2 + 2] *Cycloaddition reactions*

Fluorinated four-membered carbocycles are particularly easy to prepare because of the propensity shown by alkenes containing a $CF_2=C<$ group to participate in thermal homo- and co-cyclodimerisation reactions. The chlorofluoro-olefins $CF_2=CFCl$ and $CF_2=CCl_2$ are exceptionally reactive in this

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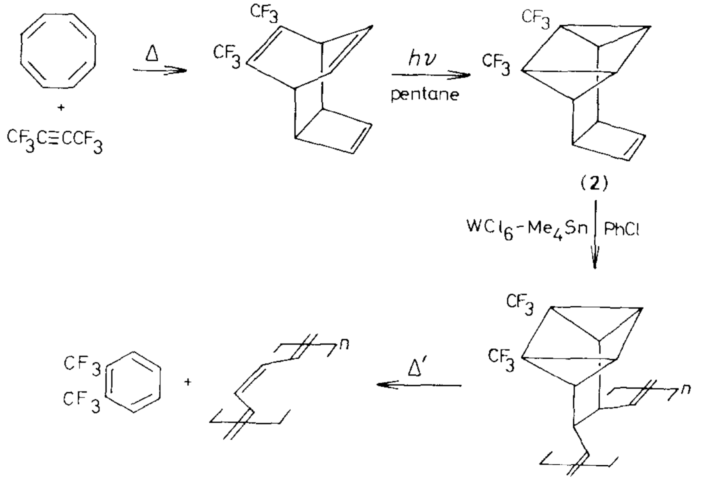
[13] Not to be confused with spectroscopic *perfluoro effects* [38], a term introduced by Brundle *et al.* who showed through systematic studies in photoelectron spectroscopy that substitution of fluorine for hydrogen in a planar molecule has a much larger stabilising effect on the σ-MOs (typically 2 - 4 eV) than on the π-MOs (often an order of magnitude smaller).

[14] For other examples, see ref. 40.

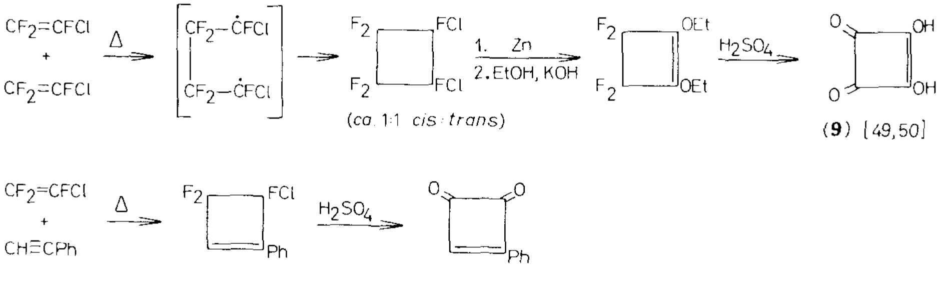
[15] See ref. 47 for details of the generation and trapping (not isolation) of an unstable bicyclic Dewar furan of the hydrocarbon class.



Scheme 11.2. An improved synthesis of poly(acetylene) via ring-opening metathesis polymerisation of 3,6-bis(trifluoromethyl)pentacyclo[6.2.0.$0^{2,4}$.$0^{3,6}$.$0^{5,7}$] dec-9-ene (2) [35].

sense, and even when given the chance to undergo a [4 + 2] reaction (Diels–Alder) often prefer to take a [2 + 2] route. In addition to providing a vast array of fluorinated cyclo-butanes and -butenes [48], this phenomenon — which distinguishes fluoroalkenes from their hydrocarbon counterparts — has been harnessed for the synthesis of non-fluorinated compounds, as exemplified in Scheme 11.3. One of the sequences shown there is the famous accidental synthesis of squaric acid (9) by Park's group [49], an event which triggered modern work in the oxocarbon field [51].

The related questions why and by what mechanism do fluoroalkenes participate in thermal [2 + 2] cycloaddition have been pondered by physical organic chemists ever since the phenomenon was discovered in the 1940s through work on the thermal depolymerisation of poly(tetrafluoroethylene)



Scheme 11.3. Synthesis of squaric acid (9) and phenylcyclobutene-3,4-dione from chlorotrifluoroethylene.

[52].[16] Studies on '1122' (1,1-dichloro-2,2-difluoroethylene) by Paul Bartlett's group did much to establish the now widely-held view [40] that a stepwise diradical-mediated mechanism operates,[17] as exemplified in the sequence leading to squaric acid formulated in Scheme 11.3. Note that Bartlett's first set of results, published in 1964 [57], were used by Woodward and Hoffmann in one of their three 1965 benchmark communications on the conservation of orbital symmetry to support the conclusion that cycloadditions which do occur in cases prohibited by their selection rules for concerted reactions must proceed through multistep mechanisms [58].

Mechanistic aspects

Radical attack on fluoro-olefins

Conventional free-radical attack on the double bonds of olefins of the fluorocarbon class generally proceeds smoothly — a feature which has been utilised *ad infinitum* for the synthesis of fluorinated compounds, including commercial polymers. The factors which control the rate and orientation of radical attack on fluorinated olefins have received considerable attention, notably in research groups directed by R. N. Haszeldine and by J. M. Tedder; the results — which have greatly enriched the field of radical chemistry — do not offer a simple qualitative theory but show that a complex interplay of polar, steric and bond-strength factors is involved [59]. That polarity is an important factor is nicely illustrated by the relative rates of addition of the radicals $CH_3\cdot$, $CH_2F\cdot$, $CHF_2\cdot$ and $CF_3\cdot$ to ethylene and tetrafluoroethylene: values for $k_{C_2F_4}/k_{C_2H_4}$ at 164 °C decrease along this series ($9.5 \rightarrow 3.4 \rightarrow 1.1 \rightarrow 0.1$). This conforms with the expected increase in electrophilicity of the methyl radical as hydrogen is progressively replaced by fluorine, and with the known susceptibility of tetrafluoroethylene to nucleophilic attack.

Fluorinated carbocations

Electrophilic attack on fluoro-olefins

That fluorocarbon olefins are much more susceptible to attack by nucleophiles than by electrophiles is in complete contrast to the familiar situation for hydrocarbon olefins, and stems from the powerful inductive ($-I$) effects associated with fluorine and perfluoroalkyl substituents in ground-state species. Thus, F-for-H substitution in the simplest (C_2) case

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[16] Low-pressure pyrolysis (600 - 700 °C at <5 mmHg) of commercial PTFE forms a convenient laboratory source of TFE in near-quantitative yield [53]. Care must be taken over the reaction conditions otherwise perfluoroisobutene, $(CF_3)_2C{=}CF_2$, a highly toxic gas, may be formed (*e.g.* ref. 54). See ref. 55 for data on the toxicities of fluoroalkenes. The ranking of perfluorinated olefins towards nucleophilic attack, *e.g.* $(CF_3)_2C{=}CF_2 > CF_3CF{=}CF_2 > CF_2{=}CF_2$, is identical with the order of comparative toxicities [LC_{50} (ppm) (4-h exposure) 0.76, 3000 and 40 000 respectively] [55].

[17] See ref. 56 for arguments proposed recently in favour of a symmetry-allowed *concerted* [$2_s + 2_a$] reaction mechanism.

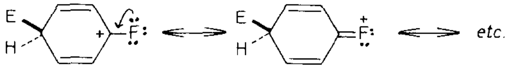
slows electrophilic attack but encourages addition of nucleophiles; for example, the ready electrophilic nitrofluorination of $CF_2{=}CH_2$ with HNO_3/HF ($\equiv NO_2^+F^-$) at −60 °C occurs six times faster than that of $CF_2{=}CHF$ under the same conditions, and much higher temperatures (10 - 20 °C) are needed to achieve a satisfactory rate of addition in the case of C_2F_4 [60].

The directions of addition, namely $CF_2{=}CH_2 \rightarrow CF_3CH_2NO_2$ and $CF_2{=}CHF \rightarrow CF_3CHFNO_2$, are rationalised by invoking a *resonance effect* (+*R*) stimulated by the attacking electrophile (electromeric effect, +*E*) and written as a mesomeric effect (+*M*) in the fully-developed cation ($>\overset{+}{C}-\ddot{\underset{\cdot\cdot}{F}}: \leftrightarrow\ >C{=}\overset{+}{\underset{\cdot\cdot}{F}}:$). Thus fluorine directly attached to a carbenium site (α-fluorine substituent) exhibits two opposing electronic effects: *polar* (electron withdrawal, $-I_\sigma$ and field) and *resonance* (π-electron donation). Although inductive electron withdrawal decreases with increasing atomic number in the halogen family, so does the conjugative (resonance) effect owing to decrease of the effectiveness of p-orbital overlap (the 2p-orbitals of fluorine are roughly the same size as carbon 2p-orbitals, unlike the outer orbitals of the heavier halogens).

In solution, the outcome is that α-halogens stabilise a carbocation in the order F > Cl > Br > I, and fluorine is usually found to be a net stabiliser compared with hydrogen. This is exemplified, for example, by the rate ratios $k_{CH_2=CXMe}/k_{CH_2=CHMe}$ for the addition of trifluoroacetic acid to propenes: 71 (X = F), 0.35 (Cl), 0.082 (Br) [61, 62]. The cation formed via protonation of 2-fluoropropene ($Me_2\overset{+}{C}F$) was the first long-lived alkylfluorocarbenium ion to be observed in solution by NMR spectroscopy [63, 64].

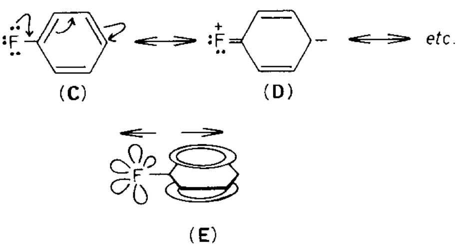
Electrophilic substitution in fluoroaromatics

Considerable attention has been paid to the effect of ring fluorine on the rate and orientation of electrophilic aromatic substitution [65]. In short, despite being the most electronegative element (and thereby displaying the most powerful −*I* effect), fluorine is an *ortho–para* director (like the other halogens) and frequently a net activator; thus, partial rate factors for electrophilic substitution at the *para* position in fluorobenzene range from 0.68 to 2.98, and for a specified reagent the value runs in the decreasing order PhF > PhCl > PhBr ~ PhI [65]. These facts can be rationalised in terms of the old accepted order of the +*R* effect (+*M* and +*E*) for halogens (F > Cl > Br > I) [66] (**A** ↔ **B**, using a σ-complex as a model for a late transition state; see Scheme 11.4). This is really a measure of the sum of the $+I_\pi$ *effect* [repulsion between a halogen's p-electrons and the π-electron cloud] and the +*M* effect [67 - 70].



(A) (B)

Scheme 11.4. Classical +*M* effect ('back-donation') in a fully developed σ-complex generated via attack of electrophile E^+ on fluorobenzene.



Scheme 11.5. (Top) Mesomeric effect, $+M$; (bottom) I_π repulsion (π-inductive effect).

Like the $+M$ effect (C ↔ D), halogen I_π repulsion (E; Scheme 11.5) induces π-charge at the *ortho* and *para* positions of a halogenobenzene and decreases in magnitude as the halogen's size increases. In ground-state situations, the combined electron-donating situation ($+I_\pi$ and $+M$) only partly neutralises the σ-inductive effect ($-I$), so fluorine in fluorobenzene, for example, is always electron-rich compared with hydrogen. Following Burdon's important paper [71], the π-inductive effect of fluorine ($+I_\pi$) has been used to explain orientational phenomena in a wealth of *nucleophilic* substitution reactions involving *poly*fluoroaryl systems. As expected, hexafluorobenzene and related aromatic fluorocarbons resist electrophilic substitution since this would require the elimination of fluorine as a cation, F^+; proton loss from pentafluorobenzene, for example, can be effected under forcing conditions, *e.g.* $C_6F_5H \rightarrow$ (with $Br_2/AlBr_3$/fuming H_2SO_4 at 60 - 65 °C) C_6F_5Br [72].

α- versus β-Fluorine substituent effects; aromatic species

Unlike α-fluorine (see above), a β-fluorine substituent exerts a strong destabilising influence on a carbocation [40, 61, 62]. In contrast to other β-halogenocarbenium ions,* β-fluoro ions do not appear to participate in 'bridging', and the cation $CH_2FCH_2^+$ has been calculated to be less stable than CH_3CHF^+ by 76.6 kJ mol^{-1} [40]. An α-CF_3 group (three β-fluorines) in a carbenium ion is enormously destabilising relative to α-methyl (three β-hydrogens); thus 3,3,3-trifluoropropene prefers to ionise to the difluoroallyl cation $[CF_2 {=\!\!-} CH {=\!\!-} CH_2]^+$ rather than undergo protonation when treated with the superacid FSO_3H [73]. Other fluorinated cations which enjoy stabilisation by resonance features other than the $+M$ effect of fluorine are known [40], including the aromatic-type species (**10**) [74] and (**11**) [75] (see Scheme 11.6).

Perfluorinated carbenium ions

No definite evidence in support of the generation of *per*fluorinated alkyl or cycloalkyl cations in normal chemical systems appears to exist

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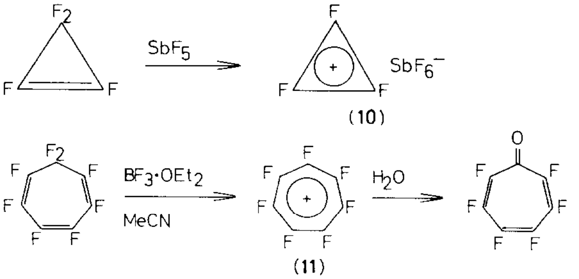
*In organofluorine chemistry the general terms halogen (halogeno) and halide refer only to chlorine, bromine or iodine and their anions, respectively.



Scheme 11.6. Synthesis of perfluorocyclopropenium hexafluoroantimonate (10) [74] and of the ^{19}F NMR-observable perfluorotropylium ion (11) [75].

[64].[18] The simplest cation of this class, CF_3^+, can be generated in a mass spectrometer [19] and by matrix photo-ionisation of trifluoromethyl halides (CF_3X; X = Cl, Br, I) or fluoroform (Ar, 15 K); the latter method has allowed the infrared spectrum of the cation to be analysed, and the results are consistent with extensive π(p–p) bonding ($\ddot{F}-\overset{+}{C}F_2 \leftrightarrow {}^+F{=}CF_2$) [76, 77]. Examination of the *gas-phase* ion chemistry of the fluoromethanes $CH_{4-n}F_n$ (n = 1 - 4) by ion cyclotron resonance techniques has established the decreasing order of carbocation stability $CHF_2^+ > CH_2F^+ > CF_3^+ > CH_3^+$ [78].

Fluorocarbenes

Not unexpectedly, π(p–p) bonding in α-fluorocarbenium ions finds an analogy in carbene chemistry. Here, predominant back-donation from lone-pair electrons on fluorine into a singlet carbene's vacant 2p-orbital is invoked to explain the electrophilicity orders $CH_2 > CI_2 > CBr_2 > CCl_2 > CF_2$ and $CH_2 > CHF > CF_2$ for singlet species, and to rationalise the fact that CF_2 and CHF are ground-state singlets whereas CH_2 is triplet stable [79]. Thermal ejection of singlet difluorocarbene from perfluoro(methylcyclopropane) to the apparent exclusion of fluoro(trifluoromethyl)carbene attests to the stabilising influence of the α-fluorine $+M$ effect [$\ddot{F}-\ddot{C}X \leftrightarrow {}^+F{=}\overset{-}{C}X$ (X = F or CF_3)] [80].

Fluorinated anions

From the early days of fluorocarbon chemistry, it was recognised that attack on unsaturated functions (C=C and C=O) by nucleophiles of many types proceeded very readily [81]. Not surprisingly, therefore, fluorocarbon chemistry is very much more richly endowed with reactions proceeding via anionic mechanisms than with processes involving cations; the subject absolutely abounds with opportunities to generate carbanions, nitranions, oxy anions, etc. All aspiring devotees of the subject must quickly learn to

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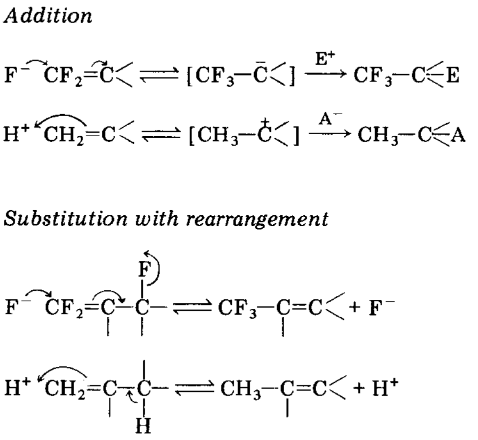
[18] Attempts to generate CF_3^+ via ionisation of trifluoromethyl halides in SbF_5/SOFCl at −78 °C yielded only CF_4. Possibly this conversion did proceed via $CF_3^+SbF_5X^-$ (X = Cl, Br, I), but the cation was not observed by NMR spectroscopic techniques [64].



Scheme 11.7. Schematic representation of the corresponding roles played by fluoride ion and proton in unsaturated fluorocarbon and hydrocarbon systems, respectively [82].

'think negative' — the reverse of the training situation in hydrocarbon chemistry — and the first lesson to be learnt is that the fluoride ion occupies a unique position as a nucleophile in fluorocarbon chemistry, analogous to that of a proton in hydrocarbon chemistry (see Scheme 11.7). Enunciated clearly by W. T. Miller in a benchmark paper 26 years ago with J. H. Fried and H. Goldwhite [82a], this concept underpins the vast amounts of synthetic work carried out worldwide since then.

Fluorocarbanions can be generated from polyfluoroalkenes and ionic fluorides under anhydrous conditions using aprotic solvents. They can then react with a whole range of nucleophile acceptors, as exemplified in Scheme 11.8. Noteworthy also is the development of the nucleophilic equivalent of the familiar Friedel–Crafts alkylation of arenes ($R_F^- + Ar_FF \rightarrow R_FAr_F + F^-$;

$$C_2F_5(CF_3)_2COH \xleftarrow{1} CF_2{=}CF_2 \xrightarrow{2} C_2F_5CO_2H$$

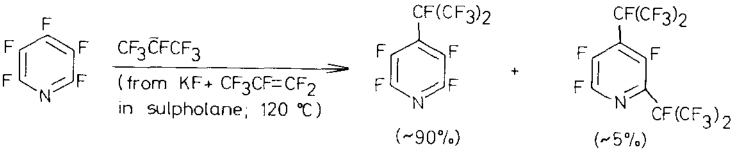
$$(CF_3)_2CFCOF \xleftarrow{3} CF_3CF{=}CF_2 \xrightarrow{4} (CF_3)_2CFCOCF_2CF_2CF_3$$

$$[(CF_3)_3C]_2Hg \xleftarrow{5} (CF_3)_2C{=}CF_2 \xrightarrow{6} (CF_3)_3CCH_2CH_2CN$$

Reagents (followed by suitable work-up)

1 CsF/diglyme then CF_3COCF_3;	2 KF/acetonitrile then CO_2;
3 CsF/acetonitrile then COF_2;	4 KHF_2/acetonitrile then n-C_3F_7COF;
5 HgF_2/dimethylformamide;	6 KF/glyme then $CH_2{=}CHCN$.

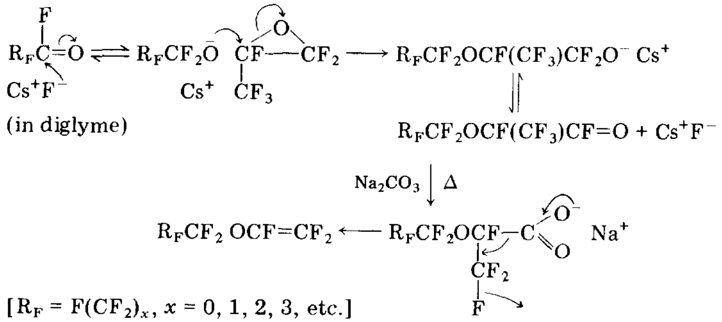
Scheme 11.8. Some syntheses involving fluorocarbanions generated *in situ* from perfluoroalkenes.



Scheme 11.9. Reaction reported in the first publication describing a fluorocarbon analogue of Friedel–Crafts alkylation of aromatics [83]. The most recent adaptation of this reaction involves the synthesis of perfluoro-[4-(thiomethoxy)pyridine] from pentafluoropyridine and $CF_2{=}S$ + CsF ($\rightarrow CF_3S^-$ *in situ*) [84].

cf. $R^+ + ArH \rightarrow RAr + H^+$) some 20 years ago by W. K. R. Musgrave and his co-worker R. D. Chambers [83] (see Scheme 11.9). Chambers has made a tremendous contribution to knowledge of perfluorocarbanion chemistry since then. One of his group's latest achievements is the direct observation by ^{13}C and ^{19}F NMR spectroscopy of the carbanions $(CF_3)_3C^-$ and $CF_3(C_2F_5)_2C^-$ generated from caesium fluoride and appropriate perfluoroalkenes [$CF_2{=}C(CF_3)_2$ and $CF_3CF{=}C(CF_3)C_2F_5$, respectively] in tetraglyme at ambient temperature [85].

Similarly, NMR-observable nitranions can be generated for use in synthesis via fluoride ion attack on C=N bonds in fluorocarbon systems [86], and perfluoroalkoxides can be procured in an analogous manner, as exemplified in Scheme 11.10. These are useful synthetic methodologies because — as a result of polar effects — not only are perfluorinated alcohols and primary or secondary (tertiary, too) amines containing α-fluorines essentially non-nucleophilic, they easily eliminate hydrogen fluoride ($CF{-}XH \rightarrow HF + C{=}X$; X = O, N). The last phenomenon is responsible for the fact that, quite unlike their hydrocarbon counterparts, fluorocarbon amines and alcohols of the above types are rare; in fact successful isolation and characterisation of the simplest members of their classes, trifluoromethylamine and trifluoromethanol, was not reported until 1977!:



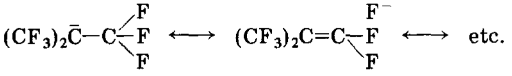
Scheme 11.10. Example of *in situ* generation of a perfluoroalkoxide [87].

$CF_3NCl_2 + 3\,HCl \rightarrow$ (at −78 °C) $2\,Cl_2 + CF_3NH_2{\cdot}HCl \rightarrow$ (with Me_3N at −30 °C) CF_3NH_2; $CF_3OCl + HCl \rightarrow$ (at −100 °C) $CF_3OH + Cl_2$ [88]. In the condensed phase, both CF_3NH_2 and CF_3OH decompose in the temperature range −30 °C to 0 °C; however, their gas-phase half-lives at *ca.* 10 mmHg pressure are at least 5 min, which has allowed IR spectra to be recorded.

Tertiary perfluorinated alcohols and alkylamines, *e.g.* $(CF_3)_3COH$ and $(C_4F_9)_3N$, are stable, easily isolable compounds. In contrast to their hydrocarbon counterparts, the former are considerably more acidic and the latter virtually non-basic — features which stem from the powerful combined inductive effects ($-I$) of the fluorocarbon groups present. In practice, perfluoro-t-butanol [pK_a 5.2 (H_2O, 25 °C)] is almost as strong an acid as acetic acid (pK_a 4.8), and readily forms an ammonium salt.

Perfluorinated C—H acids

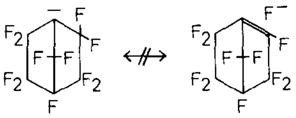
A carbon–hydrogen bond in a fluorohydrocarbon becomes more acidic (polarised) as increased numbers of perfluoroalkyl groups are carried at the C–H sites [89]. Thus the relative rates of isotope (H/D) exchange catalysed by sodium methoxide are (approximately): CF_3H, 1; n-$C_6F_{13}CF_2H$, 10; $(CF_3)_2CFH$, 10^6; $(CF_3)_3CH$, 10^{11}. Tris(trifluoromethyl)methane is a carbon acid ($pK_a \sim 21$) nearly 50 orders of magnitude more acidic than methane ($pK_a \sim 69$), and it will take up deuterium from D_2O even in a neutral medium [89, 90]. This and other hydrofluorocarbons have featured prominently in a long-standing [89] and still hotly debated controversy [40, 90, 91] concerning whether the stabilising influence of a fluorine substituent sited adjacent (β) to a carbanionic centre stems solely from polar (inductive) effects or involves also a resonance component of the no-bond type (Scheme 11.11). This is not the place to detail the pros and cons of



$$(CF_3)_2\bar{C}-CF_3 \longleftrightarrow (CF_3)_2C{=}CF_2\ F^- \longleftrightarrow \text{etc.}$$

(nine equivalent canonical forms)

Valence-bond representation of negative (anionic) hyperconjugation, using the perfluoro-t-butyl anion to illustrate this possible phenomenon [89, 90].

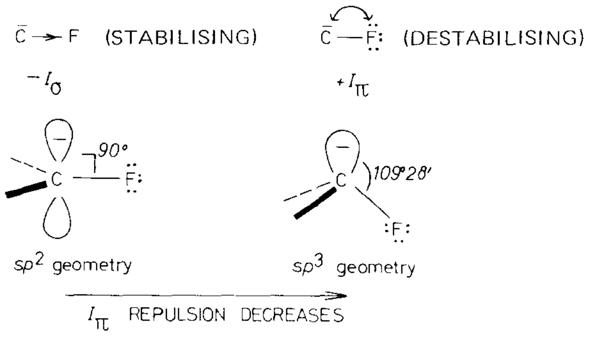


The perfluoronorborn-1-yl anion cannot benefit from such hyperconjugation, because of the geometry at the bridgehead. 1*H*-Undecafluoronorbornane is a weaker carbon acid than is tris(trifluoromethyl)methane [90].

Scheme 11.11. Negative hyperconjugation (no-bond resonance).

such 'fluorine hyperconjugation', but note that a strong recent argument in support of the significance of this phenomenon involves the molecular parameters for the perfluoroalkoxide $(Me_2N)_3S^+ CF_3O^-$ as determined by X-ray methods [92]. This TAS salt was prepared from TASF (see p. 231) and carbonyl fluoride — yet another example of the synthetic utility of fluoride addition to a multiple-bond system.

No ambiguity exists regarding the effect of a β-fluorine (or β-perfluoroalkyl) substituent on the stability of a carbanionic site: whether fluorine negative hyperconjugation intervenes or not, stabilisation always occurs and increases as the number of β-fluorines increases at the expense of hydrogen. Not so with an α-fluorine. Here, the effect can vary from modest stabilisation (compared with the standard substituent, H) to strong destabilisation, depending on the geometrical situation: the more planar the carbanion, the greater the destabilising influence. This interesting phenomenon arises through conflict between a stabilising $-I_\sigma$ effect and a destabilising π-inductive effect, $+I_\pi$ (see Scheme 11.12). The latter stems from repulsive interaction between filled p-orbitals on the halogen and the filled outer orbital on the attached carbon; like the related inductive interaction between fluorine and a π-system (see p. 237), it is classified as a $+I_\pi$ effect [71, 93, 94].



Scheme 11.12. Electronic effects of α-fluorine.

Since I_π repulsion is maximised in planar systems (Scheme 11.12), simple α-fluorinated carbanions prefer to adopt pyramidal forms. This seems to be the situation with the trifluoromethyl anion, CF_3^-, the conjugate acid of which (CHF_3, pK_a 30.5) is about 10^{40} times more acidic than methane.[19] The situation is quite different in α-fluorinated carbanions constrained to

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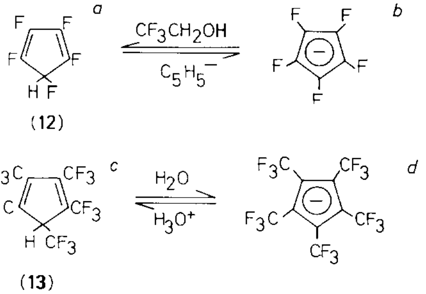
[19] Note that fluoroform is less acidic than chloroform. Acidity data for haloforms (pK_{CsCHA} values: CHF_3, 30.5; $CHCl_3$, 24.4; $CHBr_3$, 22.7; CHI_3, 22.5 [95]) and the related trifluoromethyl-ethanes and -propanes CF_3CHX_2 and $(CF_3)_2CHX$ (X = F, Cl, Br or I) have been discussed in terms of the stabilities and geometries of the conjugate bases (carbanions) involved [96]. It seems that carbanion stability is determined primarily by the degree of I_π repulsion involved, the magnitude of which for a fixed geometry decreases in the order F > Cl > Br > I.

adopt planar conformations or encouraged to do so in order to take full advantage of stabilising conjugative effects. For example, NaOMe-catalysed hydrogen isotope (H/D, H/T) exchange in fluorene is reduced by a factor of eight through the introduction of a 9-fluorine substituent, whereas 9-chloro- and 9-bromo-fluorene are 4×10^2 and 7×10^2 more reactive, respectively, than the parent hydrocarbon [97]. Amongst numerous other examples, maximisation of fluorine I_π repulsion in planar systems accounts for the classical observation that *p*-fluorophenol is less acidic than phenol [98], and for the deactivating influence of *para*-fluorines in aromatic substrates undergoing nucleophilic substitution [99]. Examples of systems not constrained structurally to planarity, but with stabilising aids maximised by such geometry, include ethyl fluoroacetates {pK_a values (polarographic): CH_2FCO_2Et, 21; CH_3CO_2Me, 24; CHF_2CO_2Et, 25 [100]} and nitromethanes {pK_a (H_2O, 25 °C) values: CH_2FNO_2, 9.55; CH_3NO_2, 10.22 [100, 101]}.

Comparison of the acidities of 1,2,3,4,5-pentafluorocyclopentadiene (12) [102] and the corresponding pentakis(trifluoromethyl) compound (13) [103] provides an illuminating example of the relative effects of α- and β-fluorine substituents on carbanion stabilities (see Scheme 11.13): the



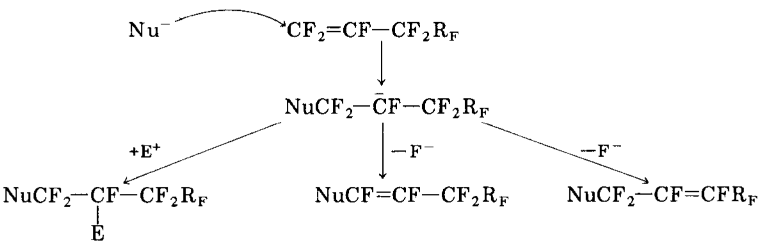
[a] More acidic than cyclopentadiene (pK_a 15.5) but less so than 2,2,2-trifluoroethanol (12.8). [b] Stabilised by electron withdrawal ($\bar{C}\rightarrow F$), but destabilised by electron repulsion ($\bar{C}\overleftarrow{-}F\!:$). [c] At least 10^{18} times more acidic than cyclopentadiene. [d] Stabilised by electron withdrawal ($\bar{C}\rightarrow CF_3$).

Scheme 11.13. Acidities of fluorocyclopentadienes.

former diene appears to be not much more acidic than cyclopentadiene itself, whereas the latter has $pK_a \leqslant -2$, making it a stronger acid than nitric acid and freely soluble in water!

Nucleophilic attack on perfluoro-olefins

Very many synthetic sequences have utilised interactions of polyfluoro-olefins with nucleophilic reagents of various types. The intermediate carbanions can react in several ways, as exemplified in Scheme 11.14. The product can either be saturated if it arises via a two-stage addition process, or, if the pathway follows an addition–elimination sequence, an alkene



Addition: where E = H, this is the main type of product with many nucleophiles and the simplest polyfluoroalkenes, *e.g.* C_2F_4, C_3F_6, except when using very strongly basic conditions.

Addition–elimination (the complete reaction is substitution of an originally vinylic fluorine): this is the main type of product with polyfluorocycloalkenes, and longer chain fluoroalkenes.

Addition–elimination with double bond shift (the complete reaction is substitution of an originally allylic fluorine): these are usually minor products.

Scheme 11.14. Nucleophilic attack on fluoroalkenes.

results by loss of fluorine as fluoride. The observed orientations of these nucleophilic attacks can be rationalised by invoking the α- and β-fluorine effects considered in the earlier sections. Schemes 11.8 and 11.9 exemplify the trapping of fluorocarbanions by electrophilic species. Wiley [104] was one of the first to demonstrate that the treatment of perfluoroalkenes with nucleophiles yields trappable carbanions [MeONa + $CF_2{=}CF_2$ + $MeOCO_2Me$ in THF → (via $MeOCF_2CF_2^-$) $MeOCF_2CF_2CO_2Me$ + $(MeOCF_2CF_2)_2CO$], and one of the latest examples of the utility of this procedure in synthesis involves the preparation of methyl 3-azido-2,2,3,3-tetrafluoropropionate by Krespan's group [NaN_3 + $CF_2{=}CF_2$ + CO_2 → $N_3CF_2CF_2CO_2Na$ (not isolated) → (with Me_2SO_4) $N_3CF_2CF_2CO_2Me$] [105].

Miller's group showed how to effect HF addition across the C=C bond of a fluorocarbon olefin via a nucleophilic mechanism ($CF_3CF{=}CF_2$ + KF in $HCONH_2$ → CF_3CHFCF_3) [82a]. Russian groups led by Knunyants (see Appendix 11.4, p. 296) have made extensive studies of the reactions of perfluoroisobutene and of the perfluoro-t-butyl anion derived from it by the action of caesium or potassium fluoride, *e.g.* $(CF_3)_2C{=}CF_2$ + MF + PhN_2^+ Cl^- (in DMF) → $(CF_3)_3CN{=}NPh$ [106]. Perfluoroisobutene, a highly toxic gas (b.p., 7 °C) [55], is extremely susceptible to nucleophilic attack and combines with water at room temperature to yield a precursor of bis(trifluoromethyl)ketene: $(CF_3)_2C{=}CF_2$ + H_2O in THF → [$(CF_3)_2CHCF_2OH$ → (—HF; rapid!) $(CF_3)_2CHCOF$] → $(CF_3)_2CHCO_2H$ → (with hot P_2O_5) $(CF_3)_2C{=}C{=}O$ [107].

A most important nucleophilic reaction of perfluoro-olefins is that which occurs with hydroperoxide or hypochlorite ion to give fluorocarbon oxiranes (epoxides), *e.g.* $XO^- + CF_2{=}CFCF_3 \rightarrow XOCF_2\bar{C}FCF_3 \rightarrow X^- + \overline{OCF_2C}FCF_3$ (14); hexafluoropropene oxide (14) is the most important compound of this class, and, as illustrated by a recent review, is a 'key compound' in organofluorine synthesis [108].

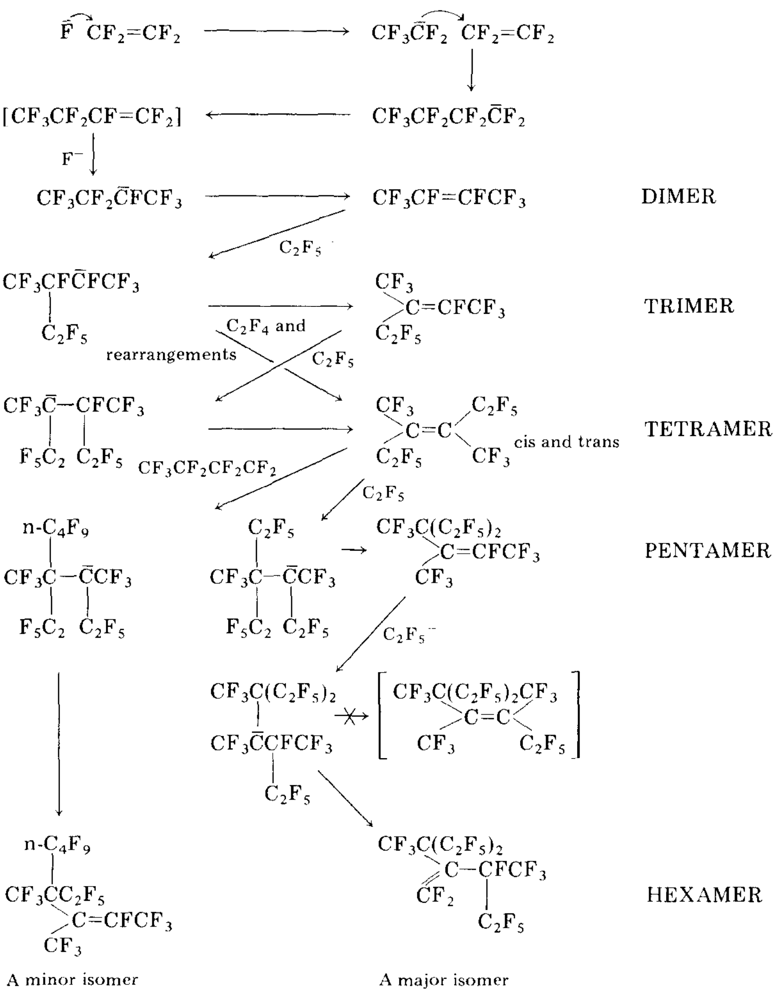
In the absence of traps, most perfluorinated carbanions will eject a β-fluorine as fluoride and collapse to alkenyl compounds (see Scheme 11.14), *e.g.* $NaN_3 + CF_2{=}CFCF_3$ in DMF $\rightarrow N_3CF_2\bar{C}FCF_3 \rightarrow F^- + N_3CF{=}CFCF_3$ [109]. Such β-elimination of fluoride occurs during fluoride-initiated oligomerisation of perfluoro-olefins [110], which is the negative equivalent of the commercially important electrophilic oligomerisation of hydrocarbon alkenes [111]. Anionic oligomerisation is involved in the synthesis of the perfluoropropene trimers $[(CF_3)_2CF]_2C{=}CFCF_3$ and $(CF_3)_2C{=}C(CF_2CF_3)$-$CF(CF_3)_2$ involved in the discovery of Scherer's radical (see Appendix 11.5). From tetrafluoroethylene, a series of oligomers with highly branched chains can be made [112] as shown in Scheme 11.15. The major hexamer isomer is hydrolysed readily to a stable and isolable fluoroketene $CF_3(C_2F_5)_2C$-$({=}C{=}O)CF(C_2F_5)CF_3$, which with NaOCl affords the α-lactone 3 (p. 233). Analogous oligomers arise from hexafluoropropene (for a summary see ref. 130b).

Perfluorinated aza-olefins

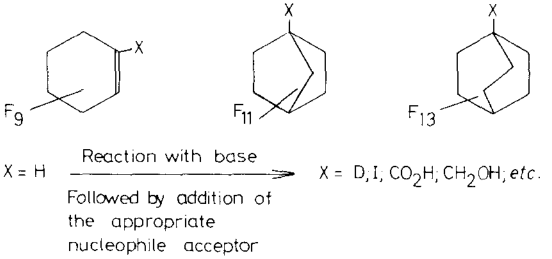
Compounds such as $CF_3N{=}CF_2$ and $\overline{CF_2(CF_2)_3CF{=}N}$ are highly susceptible to nucleophilic attack, the latter, for example, having been converted into numerous 2-substituted octafluoro-1-azacyclohexenes: $\overline{CF_2(CF_2)_3CF{=}N} + Nu^- \rightarrow \overline{CF_2(CF_2)_3CNu{=}N} + F^-$ (or HF) [Nu = $(CF_3)_2CF$, $(CF_3)_2NO$, C_6Cl_5O, N_3, etc. [113a]]. These conversions are presumed to occur via addition–elimination sequences involving nitranions, such a species derived from fluoride ion attack having been trapped with chlorine and methyl iodide: $\overline{CF_2(CF_2)_3CF{=}N} + CsF \rightarrow \overline{CF_2(CF_2)_3CF_2N^-}\ Cs^+$ (observable by ^{19}F NMR spectroscopy [86]) $\rightarrow$ (with XY; X = Y = Cl or X = Me, Y = I) $\overline{CF_2(CF_2)_3CF_2N}X$ [86, 113b].

Syntheses from perfluorinated C—H acids

In principle, fluorocarbanions should be generated by the 'ionisation' of C—H acids, but in practice most of these eliminate HF to give fluoroalkenes (apparently by means of concerted processes [114a]), so that fluorocarbanions cannot be trapped. However, if the hydrofluorocarbon structure is such that elimination of HF gives rise to a highly strained unsaturated product, then fluorocarbanions useful in synthesis can be generated. This applies with 1*H*-nonafluorocyclohexene [114b], and with the bridgehead compounds 1*H*-undecafluoronorbornane [114c] and 1*H*-tridecafluorobicyclo-octane [114d] (see Scheme 11.16). Under forcing conditions, the fluorocarbanions from the bicyclic compounds decompose to give



Scheme 11.15. Oligomerisation of tetrafluoroethylene. (Reproduced, with permission, from ref. 121.)



Scheme 11.16. Syntheses directly from hydrofluorocarbons (perfluorinated C—H acids).

strained (bridgehead) olefins as transient intermediates — these species 'violate' Bredt's rule, and that from the norbornane was the first of its type to be detected in organic chemistry [114c, d; 121].

Fluorinated radicals

Note that $+I_\pi$ repulsion occurs not only in carbanions containing α-fluorine but also in radicals. This and other fluorine-substituent effects considered to be operative in radical systems are covered in Smart's excellent review of recent developments in fluorocarbon chemistry [40]. Here we wish to point out that the very slight deviation from non-planarity shown by methyl radical increases markedly as hydrogen is progressively substituted by fluorine, and the computed equilibrium FCF angle in $CF_3\cdot$ is 112° [115a], a geometrical adjustment which minimises repulsion between lone-pair electrons on fluorine and the non-bonded electron on carbon; calculations based on ESR data reveal that the unpaired electron in $CF_3\cdot$ and $CHF_2\cdot$ occupies an orbital with 21% and 10% s-character, respectively [115b]. ESR and theoretical evidence in support of a planar geometry for the $\alpha\alpha$-difluorobenzyl radical has been advanced [115c], so the complete series $C_6H_5CF_2^*$, where $* = +$ (planar, with stabilising back-donation from fluorine), $-$ ('pyramidal', to avoid maximisation of the destabilising $+I_\pi$ effect), and $\cdot$ (planar — unlike the carbanionic case) has been studied. Since non-conjugated radicals of type $RCF_2\cdot$ adopt 'pyramidal' configurations, the phenyl group in $C_6H_5CF_2\cdot$ must provide sufficient conjugative stabilisation to offset fluorine-induced preference for non-planarity.

Steric effects

The persistence of Scherer's tertiary radical $C_2F_5(i\text{-}C_3F_7)_2C\cdot$ (see Appendix 11.5, p. 299) [116] is a kinetic effect stemming from shielding of the trivalent carbon by the sheer bulk of the perfluoroalkyl substituents. Numerous other examples can be found of phenomena ascribed to steric effects associated with perfluoroalkyl and related groups. One of the more interesting is that the low energy barrier to *syn* $\rightleftharpoons$ *anti* isomerisation of the hexafluoroacetone imine $(CF_3)_2C{=}NCF(CF_3)_2$ has been interpreted in terms of steric hindrance rather than fluorine no-bond resonance (negative hyperconjugation); the $(CF_3)_2CF$ group was suggested to be comparable in size to t-Bu [117], with CF_3 being on a level with i-Pr, according to Taft E_S values.

Saturated fluorocarbons

The existence of stable chains and rings composed of CF_2 units is made possible by the *relatively* small size of the fluorine atom (van der Waals' radius 1.47 Å in perfluoroalkanes [118]; *cf.* hydrogen, 1.20 Å, chlorine in polychloroalkanes, 1.77 Å) and the high strength of the C—F bond (see Table 11.1). However, as illustrated above the 'size' of a fluorine substituent is certainly not negligible.

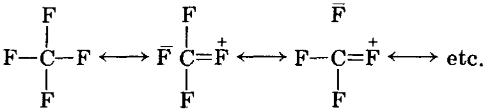
A potential energy barrier of 18.2 kJ mol^{-1} (4.35 kcal mol^{-1}) hinders mutual rotation of the CF_3 groups in hexafluoroethane compared with a barrier of 12.6 kJ mol^{-1} (3.0 kcal mol^{-1}) to free rotation around the C—C bond in ethane; furthermore, repulsive forces between fluorines on alternate carbon atoms (1,3 F–F interactions) in perfluoro-n-alkanes act to lessen the

TABLE 11.1

Some estimated bond dissociation energies/kJ mol^{-1} (kcal mol^{-1}) [120]

CF_3—F	519	(124)	CCl_3—Cl	314	(75)
C_2F_5—F	515	(123)	CH_3—H	423	(101)
$(CF_3)_2CF$—F	460	(110)	CH_3—F	452	(108)[a]
$(CF_3)_3C$—F	414	(99)	CH_2F—F	481	(115)[a]
			CHF_2—F	502	(120)[a]

[a] These values, which should be compared with $D(CF_3—F)$, are included to illustrate the strengthening of the C—F bond with increasing fluorine content of the molecules. This effect, and the accompanying marked contraction in C—F bond length {r(C—F)/Å = 1.385, 1.358, 1.332 and 1.317 for CH_3F, CH_2F_2, CHF_3 and CF_4, respectively [119]} can be rationalised in terms of double-bond no-bond resonance, *e.g.*



(12 ionic canonical forms in total).

stabilities of these compounds and facilitate conformational isomerism [120]. Thus, although it is possible to pack all the fluorines necessary to produce a saturated fluorocarbon structure around any carbon chain without significant overcrowding (an analogous situation is not possible with any other halogen), the zig-zag chain twists to relieve 1,3 F—F interactions (see refs. 120, 121). Space-filling molecular models illustrating this conformational situation (see Fig. 11.1) also reveal that the fluorine atoms in a saturated fluorocarbon form an almost impenetrable sheath, bristling with tightly held electrons, which clearly must provide the carbon backbone with excellent protection from chemical attack. As Simons put it: "The compact fluorine atom envelope in the (saturated) fluorocarbons forms such a protective coating that the rate of reaction is greatly reduced even under conditions where reactions are allowed or favoured by thermodynamics.[20] Thus it can

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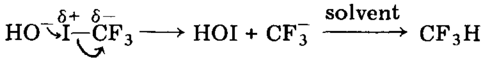
[20] As pointed out by Sharpe [122] many years ago, calculations based on thermodynamic factors predict that carbon tetrafluoride, for example, should be hydrolytically unstable mainly because the C—F bond is considerably weaker than the H—F link [570 kJ mol^{-1} (136 kcal mol^{-1})]: $CF_4(g) + 2\,H_2O(liq) \rightarrow CO_2(aq) + 4\,HF(aq)$ [ΔH^0 −180 kJ mol^{-1} (−43 kcal mol^{-1}), ΔG^0 −222 kJ mol^{-1} (−53 kcal mol^{-1})]. In practice, saturated fluorocarbons do not suffer hydrolysis below 500 °C. Nucleophilic attack of any description on saturated carbon in polyfluorinated systems is rare [40] because of steric effects and the repulsion of attacking entities by fluorine lone-pair electrons; note, however, that SET processes (single-electron transfer) can operate (ref. 40; see also Chapter 12). S_N2 Displacements on fluorine seem prohibited, but not on other halogens; the classical example here is the reaction of trifluoroiodomethane with acetonic or alcoholic potassium hydroxide at room temperature to yield fluoroform [123]:



$$HO^{-}\overset{\delta+}{I}—\overset{\delta-}{C}F_3 \longrightarrow HOI + CF_3^{-} \xrightarrow{\text{solvent}} CF_3H$$

Note the direction of polarisation of the carbon–iodine bond compared with that in methyl iodide ($\overset{\delta+}{CH_3}—\overset{\delta-}{I}$).

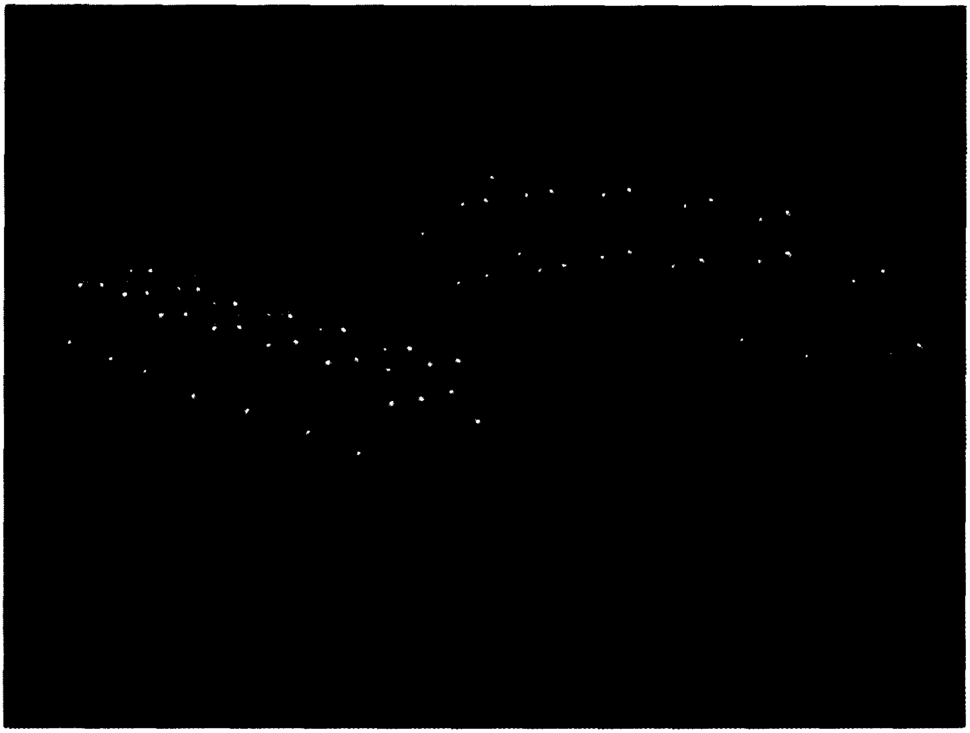


Fig. 11.1. Space-filling molecular models (Catalin) of segments of a poly(ethylene) chain (*left*; planar zig-zag conformation) and a poly(tetrafluoroethylene) chain (*right*; twisted zig-zag). The helical conformation (360° twist per 26 CF_2 groups below 19 °C) adopted by the fluorocarbon to relieve non-bonded interactions between fluorines on alternate chain carbons is clearly visible.

be truly stated that fluorocarbons have hearts of diamond and skins of rhinoceros hide" [124].

The molecular geometries of saturated fluorocarbons, coupled with the polarity of the C—F bonds, also act to endow saturated fluorocarbons with a most unusual set of physical properties. These give every evidence of extremely low intermolecular attraction — as expected if the fluorines carry a fairly high negative charge. Sanderson has suggested that the stabilities of the molecules are also related to these charges [125].

Saturated fluorocarbons are colourless, dense, apparently non-toxic[21] substances characterised by a seemingly abnormal set of physical properties

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[21] One of the earliest reliable reports on the physiological activity of saturated fluorocarbons was written by A. J. Rudge [126], a leading I.C.I. expert in fluorine chemistry who pioneered the production of UF_6 in 1940 for the so-called 'Tube Alloy Project' — the British counterpart of the 'Manhattan Project' [127]. He refers to experiments with C_7F_{14} vapour in mice which revealed that this fluorocarbon is non-toxic and virtually devoid of narcotic activity. Note that an acute problem in this type of research centres on obtaining absolutely pure specimens of fluorocarbons free from unsaturated material or hydrofluorocarbons, which tend to be toxic. The advent of gas–liquid chromatography helped matters considerably.

when compared with their hydrocarbon analogues [128]. In short, they possess relatively low boiling points which belie their molecular weight values [*cf.* n-C_5F_{12} (M.W. 288), b.p. 29.3 °C; and n-C_5H_{12} (M.W. 72), b.p. 36.2 °C], low critical temperatures and pressures, high liquid densities (1.6 - 2.0 g cm^{-3} at 25 °C) and coefficients of expansion, extremely low surface tensions (9 - 18 mN m^{-1} at 25 °C, hence liquid fluorocarbons wet any solid, including PTFE) and refractive indices (often below 1.3, *i.e.* lower than those for any other organic compound). Compressibilities are higher than for most other liquids, hence acoustic velocities are very low — typically in the range 500 to 700 m s^{-1}, compared with 1000 to 1500 m s^{-1} for most other organic liquids. Finally, their electrical properties (high dielectric strengths, high resistivities, low dielectric constants and very low dielectric losses) make them excellent insulators.

Among the most striking of the physical properties of saturated fluorocarbons are their unusual solubility characteristics, which are of great value to physical chemists working on theories of solution. Qualitatively, a fluorocarbon is generally a poor solvent, except for other substances with low internal pressures, *e.g.* other fluorocarbons, fluorocarbon derivatives and some volatile inorganic fluorides (WF_6, for example). Saturated fluorocarbons are practically insoluble in water, hydrogen fluoride and alcohols, slightly soluble in hydrocarbons, more soluble in ether and chlorocarbons, and miscible with some partially fluorinated hydrocarbons, *e.g.* benzotrifluoride, and chlorofluorocarbons, *e.g.* CF_2ClCCl_3.

Happily, from a utilitarian viewpoint, these physical properties are coupled with outstanding chemical and thermal stabilities — the feature of saturated fluorocarbon systems which was responsible for the massive synthetic effort in this area as part of the Manhattan District Project (Chapter 5). In short, perfluoro-alkanes and -cycloalkanes generally are unaffected by boiling concentrated acids and alkalis, and by oxidising and reducing agents under normal conditions. They react with glass or silica at temperatures above 500 °C to yield carbon dioxide and silicon tetrafluoride, and with molten alkali metals to give carbon and the appropriate metal fluorides — reactions which have been adapted for analytical purposes (see Appendix 11.3). Other active metals will strip fluorine from fluorocarbons at high temperatures — a phenomenon which provided the basis for the first commercially-operated route to polyfluorinated aromatic compounds nearly 30 years ago [129] (see later).

Saturated fluorocarbons are far more thermally stable than their hydrocarbon or chlorocarbon analogues (the latter are few in number), and their stability decreases with increasing chain length or, most noticeably, chain branching [120, 121]. Carbon tetrafluoride is the most stable fluorocarbon since it does not suffer the disadvantage of having a C—C bond; thus it decomposes only slowly at carbon arc temperatures (>2000 °C to give C_2F_6 and C_2F_4) and does not react with copper, nickel, tungsten or molybdenum at 900 °C. The thermal stabilities of all other saturated fluorocarbons are limited by the strengths of their C—C bonds, which are considerably weaker than C—F linkages, even in molecules not subject to strain necessarily imposed by stereochemical factors [*e.g.* $D(R_FCF_2{-}CF_2R_F) \sim 360$ kJ mol^{-1} (86 kcal mol^{-1})]. Thus, homolysis of C—C bonds in C_2F_6 and C_3F_8 is easy to observe only at temperatures above 1000 °C in platinum, and the maximum recommended working temperatures of Flutec® fluids (see p. 344) in nickel-based apparatus lie in the range 400 - 450 °C [128]. In contrast, the strained fluorocarbon perfluorocyclopropane ejects difluorocarbene when heated to about 170 °C. Systems containing bonds between tertiary carbon atoms undergo homolysis at temperatures not much above 300 °C, whilst for quaternary–tertiary C—C bonds, cleavage temperatures are even lower [120, 121].

The general properties of fluorocarbons are very often associated with fluorocarbon moieties in 'mixed' compounds, *e.g.* when carried on a hydrocarbon-type backbone. In many cases, this enables the advantageous properties of the fluorocarbon family to be conferred on materials without the need for full fluorination. The fluorinated part can be put where it is really needed.

Synthesis of organofluorine compounds

Though necessarily brief and hence extremely selective,[22] the foregoing survey of effects associated with the presence of fluorine in organic molecules should have convinced readers not conversant with the field that a massive body of knowledge concerning the synthesis and reactions of organofluorine compounds has been assembled. It should be interpolated here that very many organoelemental compounds of the fluorocarbon class have been made — an area developed right through the Periodic Table [130]. Where metallic and metalloidal derivatives are concerned, much is owed to the pioneering work of Emeléus and Haszeldine initiated at Cambridge University pre-1950[23] (see Appendix 11.7).

Even if one neglected compounds of relatively low fluorine content and concentrated solely on highly fluorinated materials (per- and polyfluorinated) a properly coordinated, multi-volume work would be required

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[22] See ref. 40 for a much more extensive and detailed account. This also includes large sections on structure-and-bonding and the reactions of saturated, unsaturated and aromatic polyfluoro compounds.

[23] The first organometallic compounds of the fluorocarbon class to be prepared were trifluoromethylmercuric iodide and its pentafluoroethyl analogue [131]:

$$R_FI + Hg \xrightarrow[\text{UV light}]{\text{heat or}} R_FHgI \qquad (R_F = CF_3,\ C_2F_5)$$

Where transition metals are concerned, the initial success involved the following reactions [132]:

$$CF_3COCl \xrightarrow{NaMn(CO)_5} CF_3COMn(CO)_5 \xrightarrow{\text{heat}} CF_3Mn(CO)_5$$

to do justice to the present situation in a comprehensive manner. The production of such an item, though badly needed, seems unlikely to occur in the foreseeable future because of financial considerations. However, a variety of useful literature is available for consultation (see Appendix 11.6), and those at the forefront of research and development are fortunate to have available *CA Selects®: Organofluorine Chemistry* (published fortnightly) and the *Journal of Fluorine Chemistry* (published monthly).

Routes to organofluorine compounds fall into two classes. One involves the construction of synthetic targets from less complex fluorinated precursors readily available commercially; such precursors are usually made via halogen-exchange methodology or electrochemical fluorination (see p. 269). In this, the 'tailor-made' approach, there need be no late fluorination stage. The second class involves C—F bond synthesis. In this chapter, attention is focused primarily[24] on applications of elemental fluorine, particularly for the conversion of hydrocarbon to fluorocarbon material. Personal success in this area would surely have given Moissan much satisfaction.

The 'tailor-made' approach

Note that since relatively few saturated fluorocarbons containing functional groups can be prepared by exhaustive fluorination procedures, and replacement of fluorine in perfluoro-alkanes or -cycloalkanes by other atoms or groups is not feasible, great importance attaches to the availability of simple chlorofluorocarbons as precursors of fluorocarbon systems. This point has already been illustrated (see p. 229) by a small (but important) selection from the great number of examples available. Without doubt, fluorocarbon chemistry owes a great deal to Swarts–Henne halogen-exchange methodology, and although much richer for the availability of fluorine, could have been developed quite extensively without it. Key compounds where synthesis is concerned have been perfluoro-olefins (notably perfluoroethene, -propene and -isobutene — all derived from chloroform[25] and perfluoroalkanecarboxylic acids (notably trifluoroacetic acid[26]), whose availability allows access *inter alia* to vital perfluoroalkyl iodides [*e.g.* trifluoroiodomethane and the telomer iodides $C_2F_5(CF_2CF_2)_nI$[27]] (see Appendix 11.7, p. 310). Some simple conversions involving heptafluorobutyric acid (a

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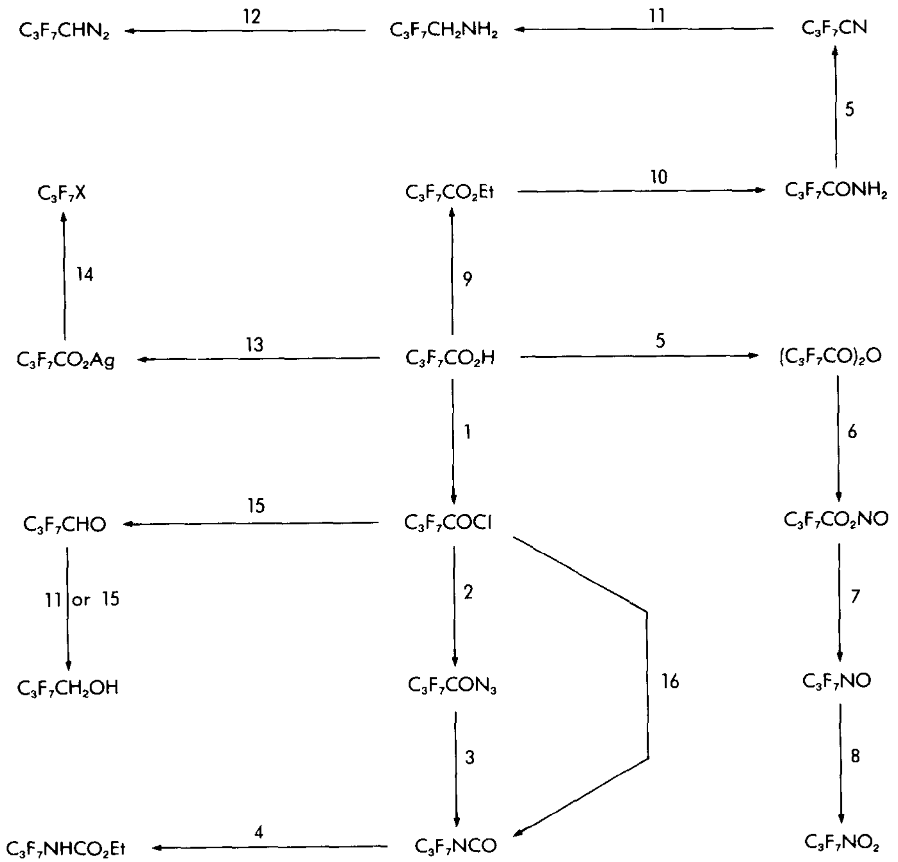
[24] See comments made earlier about fluorinating agents (p. 230); note also that Chapters 4, 5, 12, 13 and 14 contain much information on fluorination procedures.

[25] $CHCl_3 \rightarrow$ (with HF, $SbCl_5$ at 60 °C) $CHF_2Cl \rightarrow$ (at 700 °C) $CF_2{=}CF_2 \rightarrow$ (at 850 °C) $CF_3CF{=}CF_2 \rightarrow$ (at 750 °C) $(CF_3)_2C{=}CF_2$.

[26] From Simons' electrochemical fluorination of CH_3COF (see p. 269), oxidation of $CF_3CCl{=}CClCF_3$ (see p. 229) or hydrolysis of CF_3CCl_3 $\rightarrow$ [C_2Cl_6 (with HF/cat.) $CF_2ClCFCl_2 \rightarrow$ (with $AlCl_3$) CF_3CCl_3] [133].

[27] $CF_3CO_2Ag + I_2 \rightarrow$ (100 °C) CF_3I (>90%) + CO_2 + AgI (a Hunsdiecker reaction, introduced independently by Henne and Finnegan and by Haszeldine in 1950 [134]); $CF_2{=}CF_2 \rightarrow$ (with $2\,I_2 + IF_5/\Delta$) C_2F_5I [135] $\rightarrow$ (with $CF_2{=}CF_2$, peroxide/Δ) $C_2F_5(CF_2CF_2)_nI$ [136]; $CF_3CF{=}CF_2 \rightarrow$ (with $2\,I_2 + IF_5/\Delta$) CF_3CFICF_3 [135].

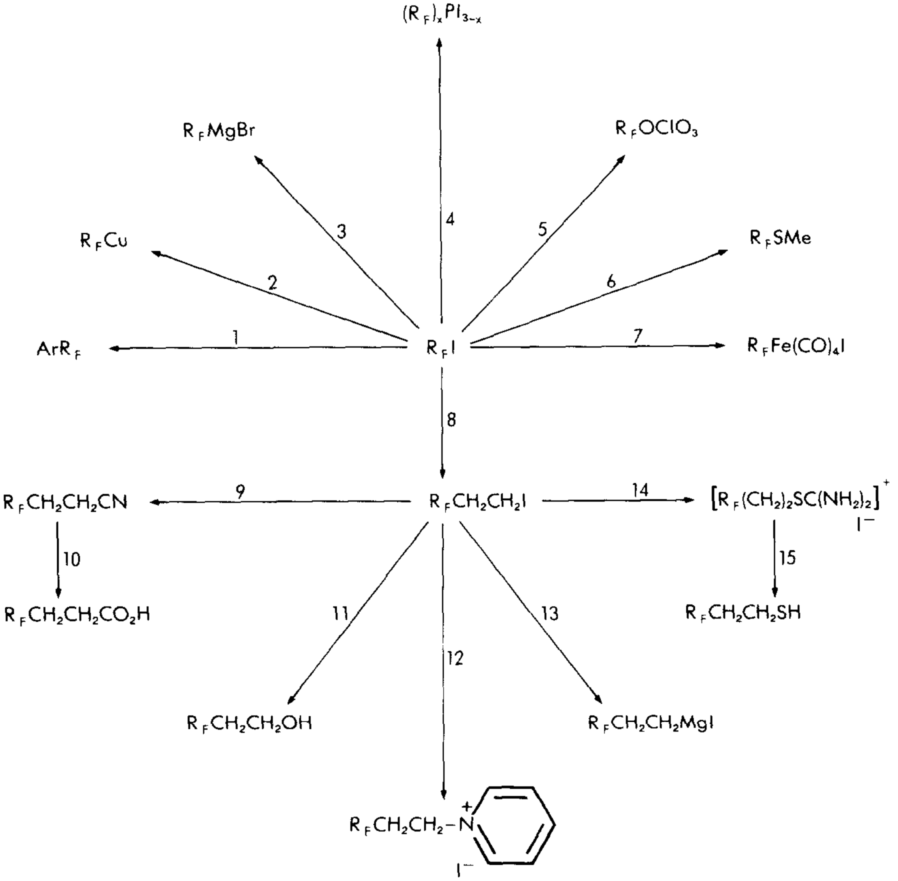
typical perfluoroalkanecarboxylic acid) and per- and poly-fluoroalkyl iodides are displayed in Schemes 11.17 and 11.18. The traditional synthetic roles of perfluoroalkyl iodides as sources of fluorocarbon radicals or anions exemplified in the latter scheme have been extended recently by Umemoto *et al.* by the development of perfluoroalkyl(aryl)iodonium trifluoromethanesulphonate (FITS) reagents, $R_F(Ar)I^+\ CF_3SO_3^-$, which deliver 'R_F^+' to nucleophilic substrates {*e.g.* $n\text{-}C_8F_{17}I + H_2O_2$ (60%)/$(CF_3CO)_2O/CF_3CO_2H \rightarrow n\text{-}C_8F_{17}I(OCOCF_3)_2 \rightarrow$ (with $CF_3SO_3H + PhH$ in $CF_2ClCFCl_2$) $n\text{-}C_8F_{17}\overset{+}{I}Ph\ \bar{O}SO_2CF_3$ [137]; $i\text{-}C_3F_7I + F_2/He \rightarrow i\text{-}C_3F_7IF_2 \rightarrow$ (with $CF_3SO_3H + C_6H_5F$ in



REAGENTS

1 PCl_5
2 NaN_3
3 Δ/toluene
4 EtOH
5 P_2O_5
6 N_2O_3
7 Δ
8 O_2/Δ
9 $EtOH/H_2SO_4$
10 NH_3
11 $LiAlH_4$
12 $NaNO_2$/HClaq
13 Ag_2CO_3
14 X_2(X=Cl,Br or I)Δ
15 H_2/Pd-C
16 Me_3SiN_3

Scheme 11.17. Conversions involving heptafluoro-n-butyric acid. (Reproduced by courtesy of Dr. M. J. Stevenson, FluoroChem Ltd., U.K.)



REAGENTS

1 ArI/Cu	4 P/Δ	7 $Fe(CO)_5$/Δ	10 H_2SO_4	13 Mg/THF
2 Cu/DMF	5 Cl_2O_4	8 C_2H_4/initiator	11 SO_3 then H_2SO_4	14 $(NH_2)_2CS$
3 PhMgBr	6 Me_2S_2/u.v.	9 NaCN	12 C_5H_5N	15 NH_4OHaq

Scheme 11.18. Some of the many synthetic applications of per- and poly-fluoroalkyl iodides. (Reproduced by courtesy of Dr. M. J. Stevenson, FluoroChem Ltd., U.K.)

$CFCl_3$) → i-$C_3F_7\overset{+}{I}(4\text{-}FC_6H_4)$ $\overset{-}{O}SO_2CF_3$ [137]; n-$C_8F_{17}\overset{+}{I}Ph$ $\overset{-}{O}SO_2CF_3$ with n-$C_{12}H_{25}SH$ + pyridine/CH_2Cl_2 → n-$C_8F_{17}SC_{12}H_{25}$, and with furan or benzene → 2-(n-C_8F_{17})C_4H_3O and n-$C_8F_{17}Ph$, respectively [138, 139]}. Polymer-supported FITS reagents can be prepared by using Nafion® perfluorosulphonic acid resin (see below) in place of triflic acid in recipes of the type shown above [140].

The important family of fluorocarbon epoxides arises from fluoroolefins. Note the commercial use of hexafluoropropene oxide (HFPO) for the synthesis (i) of the important monomer perfluoro(methyl vinyl ether) (Scheme 11.10, $R_F = F$); (ii) of perfluoropolyether fluids {Fomblin®, Galden® [Montefluos (see Appendix 11.8)], Freon E®, Krytox® (Du Pont): $F^- + HFPO \rightarrow CF_3CF_2CF_2O^- \rightarrow$ (with $n+1$ HFPO) $CF_3CF_2CF_2O\left[CF(CF_3)CF_2O\right]_nCF(CF_3)COF \rightarrow$ (with F_2, AlF_3 or SbF_5) $CF_3CF_2CF_2O\left[CF(CF_3)CF_2O\right]_nCF_2CF_3$}; (iii) of perfluorinated ion-selective membrane materials {*e.g.* $CF_2{=}CF_2 + SO_3 \rightarrow \overline{CF_2CF_2SO_2O} \rightarrow$ (with F^-) $FSO_2CF_2COF \rightarrow$ (with F^-) $FSO_2CF_2CF_2O^- \rightarrow$ (with HFPO) $FSO_2CF_2CF_2O\left[CF(CF_3)CF_2O\right]_nCF(CF_3)COF \rightarrow$ (with hot Na_2CO_3) $FSO_2CF_2CF_2O\left[CF(CF_3)CF_2O\right]_nCF{=}CF_2 \rightarrow$ (with $CF_2{=}CF_2$/radical initiator) $\sim(CF_2CF_2)_m(CF_2CF\left[OCF_2CF(CF_3)\right]_nOCF_2CF_2SO_2F)\sim \rightarrow$ (with NaOH, then HNO_3) the corresponding sulphonic acid resin [Nafion® (Du Pont)]} [108, 141a]. Japanese companies have made similar types of membrane materials carrying pendant CO_2H groups [141b]. Treatment of HFPO with Lewis acids (*e.g.* SbF_5, Al_2O_3) causes its rearrangement to hexafluoroacetone [108], thus providing an alternative to the commercial production of this interesting [120] perfluoroketone via the halogen-exchange route $CCl_3COCCl_3 + HF/CrO_2F_2$.

Aromatics

Perfluoro-benzene and -toluene were first reported in 1947 by McBee [142a], though it transpired later that the former had been synthesised in the 1930s by Désirant (a pupil of Swarts) by pyrolysis of $CFBr_3$ [142b]. Rapid progress was made in the area from the late 1950s onwards by groups in the U.K. [143] and U.S.A. [144]. One of the former synthesised fluoroarenes by exhaustive fluorination of aromatic hydrocarbons using CoF_3 (see p. 267) followed by recreation of aromatic unsaturation via dehydrofluorination or defluorination [129], whilst the latter used the Désirant reaction. Pentafluoropyridine and related compounds were made available soon after [145]. Large numbers of compounds containing many functional groups were synthesised by S_NAr-type reactions (see Scheme 11.19). The pattern of directional effects in nucleophilic substitution reactions of polyfluoroaromatic and -heterocyclic compounds was then established [120, 121, 143, 145]. Electrophilic replacements of isolated hydrogens and free-radical reactions have also been used, and a whole vast field of polyfluoroarene chemistry has been built up.[28]

A special feature of highly fluorinated arenes and heteroarenes is their ability to undergo photochemical valence-bond isomerisation, hexafluorobenzene yielding one of the first products of this type [147], which had a *para*-bonded 'Dewar-benzene' structure. Other (more complex) products are also formed [130b], the range from hexakis(trifluoromethyl)benzene being indicated in Scheme 11.20. This is another case where organofluorine chemistry has made a great contribution to progress in general organic chemistry.

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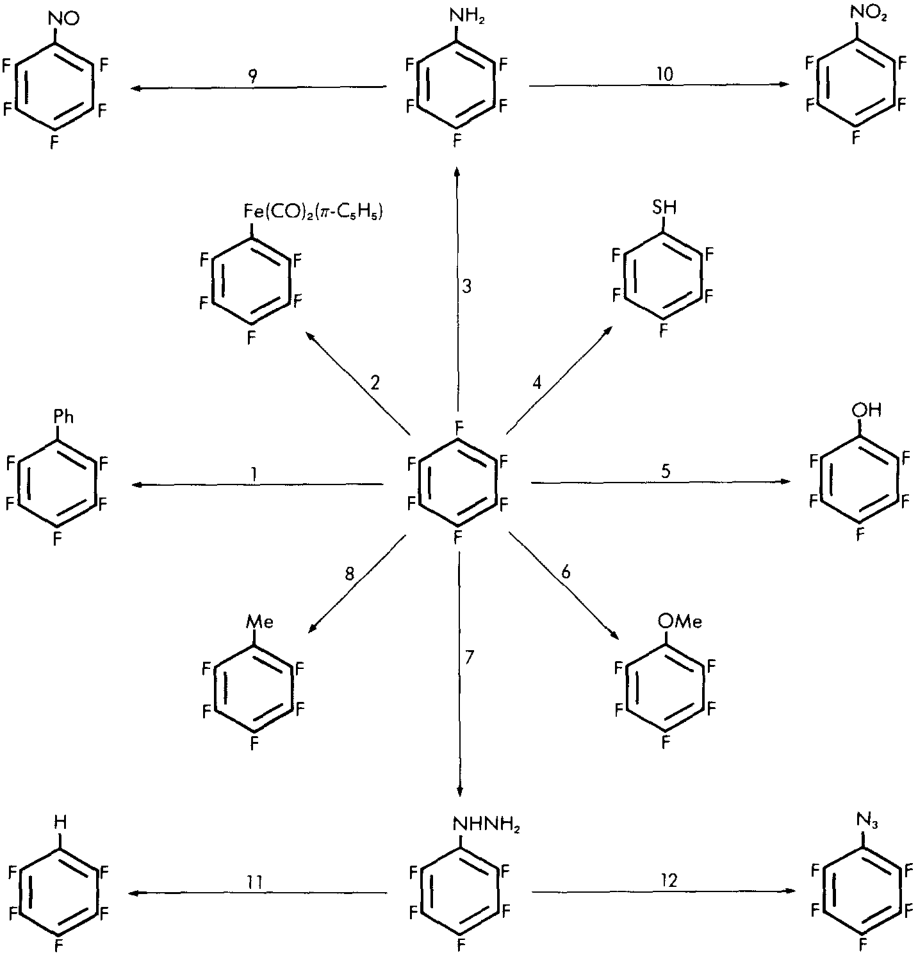
[28] A very significant contribution in this area has been made by G. G. Yakobson and his co-workers at the Institute of Organic Chemistry, Novosibirsk, U.S.S.R. [146]. They have had particular interests in nucleophilic substitutions and also in pyrolytic reactions with polyfluoro-aryl and -heteroaryl systems.



REAGENTS

1 PhLi

2 $Na+[\pi-C_5H_5Fe(CO)_2]-$

3 NH_3

4 NaSH

5 KOH

6 NaOMe

7 $N_2H_4 \cdot H_2O$

8 MeLi

9 HCO_3H

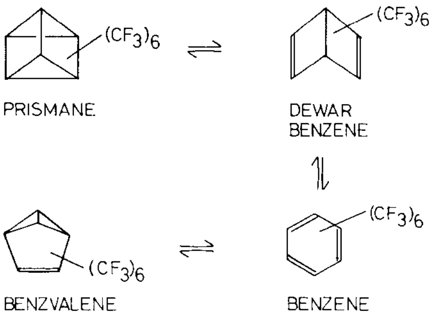
10 CF_3CO_3H

11 $CuSO_4aq$

12 $NaNO_2/HClaq$

Scheme 11.19. Synthesis of pentafluorophenyl derivatives via nucleophilic attack on hexafluorobenzene. (Reproduced by courtesy of Dr. M. J. Stevenson, FluoroChem Ltd., U.K.)

The initial commercialisation of per- and poly-fluoroaromatic chemistry relied on the CoF_3 process, but halogen-exchange methodology has taken over [148]. Now made commercially by heating hexachlorobenzene and pentafluoropyridine respectively with potassium fluoride (no solvent) at 450 - 500 °C, hexafluorobenzene and pentafluoropyridine have become readily available. Note that the characteristic susceptibility of perfluoroarenes to nucleophilic attack forms the basis of the recently demonstrated

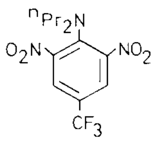


Scheme 11.20. Structures of valence-bond isomers arising from perfluoroarenes.

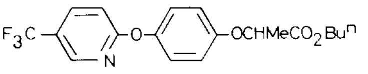
use of octafluorotoluene or pentafluoropyridine as novel reagents for the selective protection of phenolic and alcoholic functions in steroids [149a]. Pentafluorophenol can be usefully employed to protect carboxyl functions as pentafluorophenyl esters during the synthesis of peptides [149b].

Exchange of nuclear chlorine for fluorine in aromatic substrates activated towards S_NAr reactions (using KF in hot sulpholane, for example) or of side-chain chlorine in benzotrichloride or its derivatives (using Swarts-type reagents) is used extensively on a commercial scale to produce intermediates of low fluorine content for the production of pesticides, pharmaceuticals and dyestuffs [150]. The manufacture of diflubenzuron (**15**) (insecticide) and the important herbicide trifluralin (**16**), for example, involve respectively the conversion of 2,6-dichlorobenzonitrile to its difluoro analogue with potassium fluoride and nitration of *p*-chlorobenzotrifluoride procured from *p*-chlorobenzotrichloride and HF/SbF_3Cl_2. As a class, BTF (benzotrifluoride) derivatives have proved enormously successful as pesticides, and this has stimulated a recent search for unique agrochemicals of the (trifluoromethyl)pyridine class [151]; the herbicide fluazifop-butyl (**17**) is one of the fruits of this search. The most recent advance where fluorinated agrochemicals are concerned involves the organosilicon fungicide DPX-H6573 (**18**), which is now undergoing extensive field trials [152].

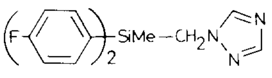
(**15**) diflubenzuron



(**16**) trifluralin



(**17**) fluazifop-butyl



(**18**) DPX-H6573

Both diazofluorination of aromatic amines in AHF [153a] and the Balz–Schiemann fluoroborate route to nuclear fluoroaromatics (see Chapter 4) have been developed commercially, the latter on an impressive scale recently for the production of the diarylmethane precursor of the PEEK monomer $(4\text{-}FC_6H_4)_2CO$ (see p. 232) via the isolation and subsequent pyrolysis of the bis-tetrafluoroborate $CH_2(C_6H_4N_2^+\text{-}4\ BF_4^-)_2$ [153b].

Classification of fluorinating agents for C—F bond synthesis

Broadly speaking, fluorinating agents can be divided into two classes, according to their activities and hence the degree of control which can readily be exercised over them:

Class I is based on hydrogen fluoride, and compounds like KF, SbF_3 and SF_4, derived from it. There are now many sophisticated variants of reagents in this class.

Class II comprises elemental fluorine, and compounds made by the use of it, such as halogen fluorides (*e.g.* ClF_3, BrF_3) and certain high-valency metal fluorides (*e.g.* CoF_3, AgF_2).

Class I comprises the so-called mild fluorinating agents. These allow fluorine to be introduced at specific sites in organic molecules, and are categorised as means for achieving *partial fluorination*. As indicated previously (see p. 231), this class has received the lion's share of attention during the past 30 years, and there is no shortage of review literature covering developments in this important area [20]. Even Class II reagents have been re-examined from this point of view, with the result that the potential of elemental fluorine as a specific fluorinating agent under appropriate circumstances has now been recognised. Furthermore, xenon difluoride and reagents containing O—F or N—F bonds which require elemental fluorine for their production have achieved importance for specific substitutions. In this way fluorine has become involved with both Class I and Class II fluorinating agents. Such developments have been discussed lately by Haas and Lieb [154].

It is beyond the scope of this chapter to discuss all the various reagents of Class I (but see footnote 24 on p. 252) and only developments using fluorine itself will be covered.

Class II consists of so-called vigorous fluorinating agents which are capable of substituting *all* hydrogen and functional groups in an organic molecule by fluorine and saturating all multiple C—C bonds or aromatic systems. It is to this class, therefore, that one looks for reagents suitable for converting hydrocarbons to saturated fluorocarbons. With care, it is possible in certain cases to restrict the amount of fluorine introduced by these reagents and thus obtain polyfluorinated products containing some hydrogen (hydrofluorocarbons) or a functional group. However, the most important direct method for the conversion of hydrocarbon derivatives to a functionalised fluorocarbon system is the Simons process — an electrochemical technique based on AHF, but which is best grouped with Class II reagents. These are categorised as means for achieving *exhaustive fluorination*. Commercial interest in exhaustive fluorination of organic substrates via the use of elemental fluorine, cobalt trifluoride or the Simons' electrochemical procedure has now reached a record level and continues to heighten.

Class I: specific fluorinations involving elemental fluorine; delivery of 'F^+'

Some examples of the types of specific C—F bond synthesis which can be achieved with elemental fluorine and reagents derived directly from it are shown in Schemes 11.21 and 11.22; others can be found in Chapter 13, notably the synthesis of the important anti-cancer agent 5-fluorouracil (Scheme 13.1). Note the ability of each of the reagents displayed in Scheme 11.21, and of fluorine itself under appropriate conditions (Scheme 11.22), to behave as *electrophilic* fluorinating agents. The mechanism by which 'positive fluorine' is delivered provides a subject of on-going controversy [184] and experimentation [185]; it is touched on in a recent review [163] of specific fluorination, which indicates that perchloryl fluoride ($FClO_3$),[29] xenon difluoride, trifluoromethyl hypofluorite (fluoroxytrifluoromethane, CF_3OF) and fluorine itself are the most important commercially-available electrophilic fluorinating agents. Naturally, nobody believes that even solvated fluoronium ions are present in any of the systems so far encountered: Sharpe [122] pointed out this improbability years ago when he compared the value of 420 kcal mol^{-1} (1760 kJ mol^{-1}) for the molar enthalpy of formation of gaseous F^+ with the values for the other halogens [Cl^+, 327; Br^+, 301; I^+, 268 kcal mol^{-1} (1370, 1260 and 1120 kJ mol^{-1} respectively)].

Class II: exhaustive (per-) fluorination

Currently, the most important methods for converting hydrocarbon entities directly into fluorocarbon materials are treatment with elemental fluorine or cobalt trifluoride and Simons' electrochemical fluorination (ECF). Safe techniques for manipulating anhydrous hydrogen fluoride (for ECF) and fluorine (for direct use or for the generation of CoF_3) are very well documented nowadays [186, 187], so apart from the expense, there is no reason why any skilful practitioner of preparative chemistry should not be able to undertake exhaustive fluorinations.

Unlike the pioneers who blazed (an appropriate verb!) the trails of direct fluorination methodology (Chapter 4), modern researchers do not have to spend most of their time dealing with temperamental fluorine cells: they simply purchase steel cylinders containing neat fluorine or fluorine–nitrogen blends [187], or use reliable, trouble-free, medium-temperature cells like those developed by Imperial Chemical Industries [127, 188].

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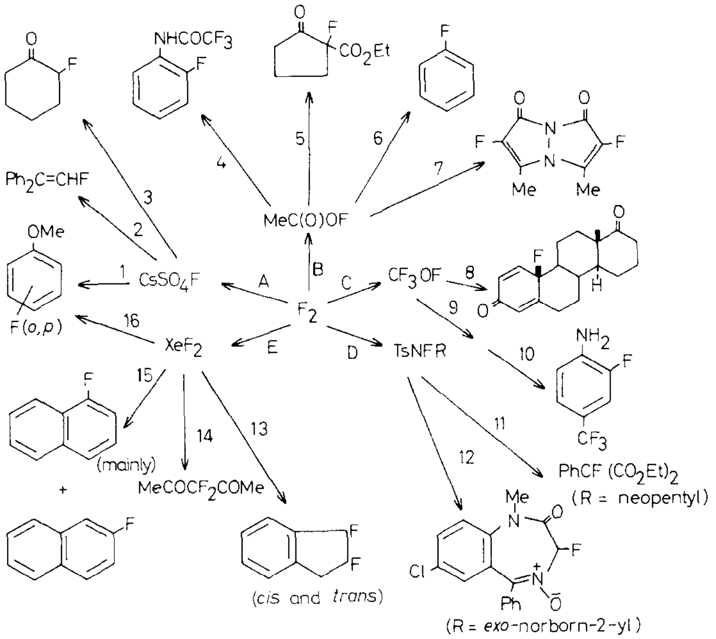
[29] A hazardous gas (b.p., −46.7 °C) capable of being manufactured via electrolysis of sodium perchlorate dissolved in AHF or treatment of potassium perchlorate with fluorosulphuric acid [166]. For reviews of its application as a specific fluorinating agent, see refs. 20, 154 and 166, the last of which emphasises the danger associated with this compound.



Substrates

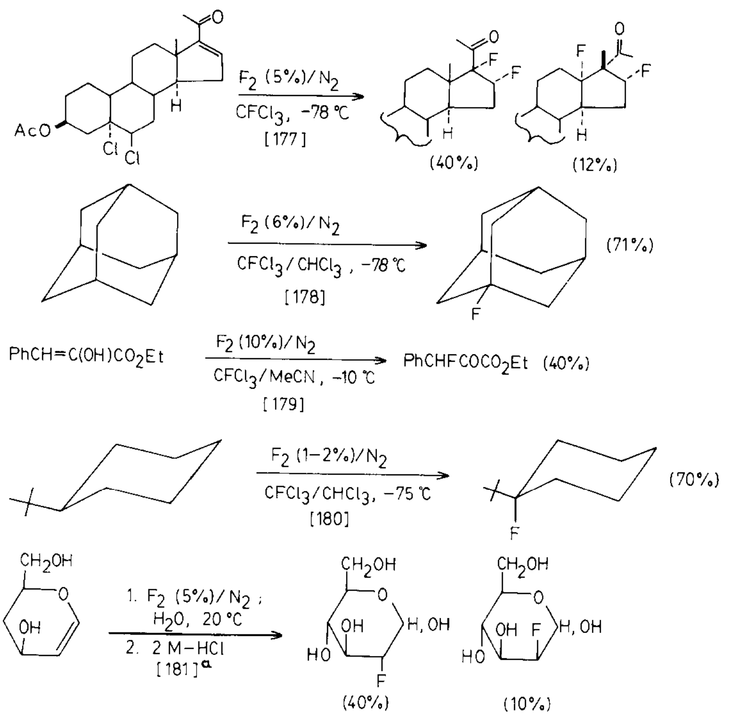
1 PhOMe in MeCN [156, 158]
2 $Ph_2C=CH_2$ in CH_2Cl_2 [159]
3 $\overline{CH_2(CH_2)_3C}H=COCOMe$ in CH_2Cl_2 [159]
4 $PhNHCOCF_3$ in $CH_2Cl_2/CFCl_3$ [162]
5 The corresponding sodium enolate [163]
6 PhHgOAc in AcOH [164]
7 *syn*-(Methyl,hydro)bimane in $CHCl_3/MeNO_2$ [165]
8 Oestrone methyl ether or oestrone acetate in $CFCl_3$ [169]
9 $4\text{-}CF_3C_6H_4NHAc$ in HOAc [170]
10 EtOH/conc. HCl [170]
11 $Ph\bar{C}(CO_2Et)_2\ Na^+$ [from $PhCH(CO_2Et)_2$ + NaH in THF] [171]
12 The anion derived from the corresponding benzodiazepinone N^4-oxide and KH in THF [171]
13 Indene in CH_2Cl_2 [173]
14 $CH_3COCH_2COCH_3$ in CH_2Cl_2 [174]
15 Naphthalene in CH_2Cl_2 [175]
16 $C_6H_5OCH_3$ in CH_2Cl_2 [176]

Scheme 11.21. Some electrophilic fluorinations with reagents prepared directly from elemental fluorine.

[A] This ionic hypofluorite (caesium fluoroxysulphate, $Cs^+\ FOSO_3^-$) can be prepared by passing a fluorine–nitrogen mixture (20% F_2) into a cold (—5 °C to 0 °C) aqueous (2M) solution of caesium sulphate [155]. The dry salt must be handled carefully: it detonates when heated to *ca.* 100 °C [155], when compressed [156] and when touched with a metal spatula [155, 156]. It is said to be 'stable' when stored at 0 °C in dry polyethylene containers [156, 157].

[B] Acetyl hypofluorite, an unpredictably explosive pale-yellow liquid (extrapolated b.p., 53 ± 6 °C [160]), has been used extensively as an electrophilic fluorinating agent — *without isolation* — since its introduction as a synthetic tool in 1981 by Rozen and Lerman [161]. Usually generated via passage of nitrogen-diluted F_2 through NaOAc or NH_4OAc in HOAc or $CFCl_3$/HOAc, or through a bed of KOAc•2HOAc, acetyl hypofluorite is particularly useful for the synthesis of ^{18}F-labelled compounds for positron-emission tomography (see Chapter 13).

(continued)



Scheme 11.22. A few of the many specific 'electrophilic' fluorinations achieved with elemental fluorine.

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[a] Direct liquid-phase fluorination of organic substrates dissolved in water was pioneered by Grakauskas some 25 years ago, following his discovery that the passage of fluorine into aqueous urea gives *N,N*-difluoro-urea, NF_2CONH_2 [182]. A whole range of *N*-fluoro compounds has been made in this manner, including *N,N*-difluoroalkylamines, *e.g.* cyclohexylamine in $NaHCO_3(aq)/CFCl_3$ at *ca.* 0 °C → c-$C_6H_{11}NF_2$ (66%) [183].

Either way, of course, a strict protocol must be established for carrying out the work, and carefully designed apparatus built from metal, fluoropolymer and — where appropriate — glass or silica components is required.

Exhaustive fluorination requires mainly all-metal equipment. Most of the common constructional metals (except tin or lead and their alloys) are satisfactory for use with fluorine at temperatures and pressures not greatly

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[C] Trifluoromethyl hypofluorite is a hazardous gas (b.p., −95 °C) which must be manipulated with great care [166]. Obtainable via reaction of elemental fluorine with carbon monoxide or carbonyl fluoride, its use as an electrophilic fluorinating agent was pioneered in Barton's group [167]. For information on long-chain perfluorinated fluoroxy compounds see ref. 168.

[D] Prepared by bubbling a fluorine–nitrogen mixture (1 - 5% F_2) through a solution of *p*-$MeC_6H_4SO_2NHR$ in $CFCl_3/CHCl_3$ at −78 °C [171].

[E] The use of xenon difluoride (see Chapter 7) as a specific fluorinating agent in organic chemistry owes much to the pioneering studies of Hyman, Shaw and Filler [172].

above ambient; and copper tubing is widely used to make connections between fluorine sources and laboratory reactors. As the operating temperature is raised, freedom of choice becomes much more restricted. Mild and stainless steels perform well at temperatures up to 200 °C with HF-free fluorine, and nickel [or its alloy with copper (mainly), Monel] gives excellent service up to 450 °C [189]. Sintered alumina can be used up to at least 800 °C. Platinum, once considered to be *the* metal for use with fluorine, is quite unusable at 400 °C. Note, however, that the corrosion resistance of all materials depends upon careful passivation of the system with fluorine once all grease, dirt or other foreign materials which could ignite on contact with the halogen have been removed by conventional means. Pickling of a nominally clean apparatus with fluorine–nitrogen mixtures, and finally neat fluorine, removes the last traces of any contaminant and produces an impervious fluoride film on metal surfaces [187]. In the laboratory, small quantities of fluorine (*e.g.* in exit gases from reactors) can be destroyed by passage through scrubbers containing granular alumina, calcium oxide or soda-lime [187], or sodium iodide ($2\ NaI + F_2 \rightarrow 2\ NaF + I_2$) if the amount needs to be determined. Burning with fuel gas or charcoal and scrubbing with caustic solutions are practiced on an industrial scale, care being taken with the last method to ensure complete destruction of oxygen difluoride produced [187].

Direct fluorination of hydrocarbon material

Successful direct fluorination of organic molecules depends on the control of the rate at which conversion of material is allowed to proceed and efficient dissipation of the large amounts of heat generated, particularly during the conversion $\geqslant CH + F_2 \rightarrow \geqslant CF + HF$, which is exothermic enough overall to cause scission of C—C bonds. This has been well known since the work of Bockemüller in the 1930s (see Chapter 4).

Gaseous fluorine reacts readily with hydrocarbons, progressively replacing hydrogen atoms and saturating multiple bonds present via chain reactions, as illustrated in Scheme 11.23 for hydrogen replacement in an alkane [190]. These are very efficient because the postulated molecule–molecule initiation step (b) and the propagation steps [(c) and (d)] have negative free-energy changes; hence the reactions can occur spontaneously *even in cooled systems*, despite the negligible dissociation of molecular fluorine under such conditions (F_2 at 1 atm pressure is only 1% dissociated into atoms at *765 °C*). Naturally at elevated temperatures — created purposely or inadvertently in reaction 'hot spots' — the importance of initiation involving homolysis of molecular fluorine increases. Note that initially, local fluorine concentrations must be kept very low (by the use of nitrogen or helium as a diluent), not only to avoid flame and explosion, but also to minimise the occurrence of termination step (e) because this is the only individual process that liberates enough energy to break a C—C single bond [strengths range from 350 to 370 kJ mol^{-1} (84 - 88 kcal mol^{-1})]. This important factor, and others, relating to the successful control of direct

	$\Delta G_{298\,\mathrm{K}}/\mathrm{kJ\,mol^{-1}}$	$\Delta H_{298\,\mathrm{K}}/\mathrm{kJ\,mol^{-1}}$
Initiation[30]		
(a) $F_2 \longrightarrow 2\,F\cdot$	124	158
(b) $F_2 + RH \longrightarrow R\cdot + HF + F\cdot$	−24	16
Propagation		
(c) $RH + F\cdot \longrightarrow R\cdot + HF$	−151	−141
(d) $R\cdot + F_2 \longrightarrow RF + F\cdot$	−285	−289
Termination		
(e) $R\cdot + F\cdot \longrightarrow RF$	−408	−447
(f) $R\cdot + R\cdot \longrightarrow R_2$	−294	−351
Overall change		
$F_2 + RH \longrightarrow RF + HF$	−435	−430

Scheme 11.23. Some thermodynamic data (based on values for methane) for steps involved in the radical fluorination of an alkane [190]. To convert kJ mol^{-1} to kcal mol^{-1}, divide by 4.184.

exhaustive fluorination of hydrocarbons have been discussed in detail by Lagow and Margrave [190], who, in 1970 [192], rejuvenated interest in the method and introduced the now well-known technique known as LaMar fluorination. This cryogenic method, together with aerosol, jet and porous-tube fluorination are the most important direct methods now available. Each one is defined briefly below, and the first two form the subjects of Appendices 11.9 and 11.10, respectively.

LaMar fluorination [190]

A sample of a liquid or gaseous hydrocarbon material to be fluorinated is injected into the front compartment of a multi-zone, cryogenic, tubular, nickel reactor packed with copper filings or turnings, which not only act as a heat sink but ensure that a thin film of solidified organic material is exposed to the (initially very dilute) fluorine. As the replacement of hydrogen by fluorine proceeds, the temperatures of the zones are increased and the dilution of the fluorine is decreased; the more highly fluorinated the sample of organic material becomes, the more rapidly it moves through the reactor because of the increase in volatility. The technique is best illustrated by reference to the latest report [193], which concerns the direct fluorination of branched-chain ethers. A four-zone reactor was used and 1 cm^3 (0.72 g) of

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[30] Fluorine homolysis induced by molecular collisions of type (b) has an olefinic counterpart, namely $\rangle C{=}C\langle + F_2 \rightarrow \rangle CF{-}\dot{C}\langle + F\cdot$ [$\Delta H \sim -5.4$ kJ mol^{-1} (-1.2 kcal mol^{-1})], proposed by Miller and Dittman in 1956 [191] to account for results achieved in studies on the low-temperature fluorine-sensitised oxidation of tri- and tetra-chloroethene. The deleterious effect of oxygen present in impure fluorine (or adventitiously admitted as air) upon reactions of the halogen with organic compounds — even at low temperature — was thereby established. The absolute validity of the Miller initiation mechanism has not been established yet.

di-isopropyl ether, for example, was injected. Fluorine (0.25 $cm^3 min^{-1}$) diluted with helium (25 $cm^3 min^{-1}$) was passed into the reactor for 1 d with zones 1 and 4 cooled to −78 °C, and zones 2 and 3 held at −90 °C. The F_2/He ratio was increased every 24 h, until by day 8 neat halogen was being employed at a flow rate of 2.0 $cm^3 min^{-1}$; on that day, the zone temperatures were ambient (1), ambient (2), −78 °C (3) and −78 °C (4). The temperature of zone 2 was increased from −90 °C to −78 °C on day 3, and from thence to ambient after day 7; zone 3 was warmed from −90 °C to −78 °C on day 7. Fractionation of the product provided 1.22 g of crude perfluoro(di-isopropyl ether), $(CF_3)_2CFOCF(CF_3)_2$, which required purification by GLC.

Solid substrates — including polymers — are ground to a fine powder (<100 mesh), placed in nickel boats, and fluorinated in open tubular reactors. In this way, tetraphenylmethane (0.26 g) has been converted to its perfluoro analogue $(c\text{-}C_6F_{11})_4C$ in 96% yield during 9.5 d, with the reactor held at −80 °C for the first 2.5 d, room temperature for the next 4 d and 50 °C for the last 3 d [194]. Also, numerous high-molecular-weight polymers have been subjected to LaMar fluorination — complete, or almost complete, fluorination of finely powdered (<100 mesh) poly(ethylene), poly(propylene), poly(ethylene-*co*-propylene), poly(isobutylene), poly(acrylonitrile), poly(styrene), etc. having been achieved at room temperature [195].

Lagow is confident that the LaMar method, hitherto described only in small-scale terms, can and will be commercialised (see Appendix 11.9). Many will be sceptical of this assertion.

Aerosol fluorination [196]

Adcock, who helped develop the LTG (low-temperature gradient) version of the LaMar slow-batch process, has invented a flow version which enables high degrees of fluorination to be achieved over a much more reasonable time scale. The technique, described in Appendix 11.10, has enabled — for example — 1.39 g (22% yield) of perfluoro(methoxycyclopentane) to be obtained from 2.05 g methoxycyclopentane fed continuously to the reactor during 5.5 h [197].

Adcock seems convinced that his method can be scaled up.

Porous-tube fluorination

Recent patents [198] describe the successful direct fluorination of volatile organic materials on a laboratory scale in a concentric-tube, vapour-phase reactor comprising a porous metal [Inconel (Ni–Cr–Fe alloy), nickel, or copper] or fused alumina (alundum) tubular probe, closed at one end and shrouded by an impervious, open-ended, stainless-steel jacket (annular space 0.95 cm). Pressurised fluorine, usually diluted with sulphur hexafluoride, helium or nitrogen, is fed into the porous insert and diffuses through the walls to meet gaseous or vaporised organic material (also diluted, if necessary) flowing through the outer tube at rates in the range 0.05 - 0.5 mol h^{-1}. The temperature of the outer surface of the porous tube rises rapidly as reaction commences, and a gradient becomes established along the tube. Good results have been claimed for the conversion of acetone to perfluoroacetone, and of propane or propene (and perfluoropropene) to perfluoropropane.

Jet fluorination

Of the four methods under discussion here, this is the oldest and stems from the on-going efforts of Bigelow's group after World War II to develop satisfactory vapour-phase flow fluorinators. This work, which has been reviewed by Tedder [199], led to the abandonment of packed reactors (see Chapter 5) and the introduction by Tyczkowski [200] of a novel open-tube apparatus in which nitrogen-diluted hydrocarbon could be introduced via a jet-action device into an atmosphere of fluorine, itself diluted with reactor gases circulated by jet-pump action. Later, an advanced triple-jet fluorinator was described in which both the organic sample and the fluorine were admitted to the reaction zone through turbulent jets [201].

Jet fluorination seems to be the method of choice for the conversion of low-molecular-weight hydrocarbons to their fluorocarbon counterparts. It is used by Tyczkowski (see Fig. 11.2) on a semi-technical scale to convert propene into perfluoropropane, a gaseous fluorocarbon (b.p., −38 °C) valued as a dry (plasma) etchant in the microelectronics industry (see ref. 202 and Appendix 11.11).

Surface fluorination of polymers

As mentioned above, hydrocarbon polymers can be converted slowly to fluorocarbon analogues by treating them with fluorine heavily diluted with nitrogen or helium, followed by gradient changes in fluorine concentration, *i.e.* by a LaMar procedure. With substrate sizes greater than 100 mesh a hydrocarbon core is retained, and fabricated items such as poly(ethylene) bottles can be given a 'fluorocarbon skin' of at least 0.1 mm thickness [203]. Elastomeric items have also been surface-fluorinated *e.g.* surgical gloves (inner surfaces, to remove the need for talcum powder), O-rings and gaskets for corrosive environments, and blades for windscreen wipers (rendering them sunlight-and-ozone resistant) [203, 204]. A most remarkable example of the commercialisation (see Appendix 11.9) of such postpolymerisation fluorination of hydrocarbon monomers is the blow-moulding of polyethylene (HDPE) containers with F_2/N_2 blends (1% fluorine) at 60 psi, to provide — in just a few seconds at the fabrication temperature — containers with outstanding resistance to non-polar solvents [205]. A bright future seems assured for such surface-fluorinated bottles (for paint and paint thinners, lighter fluid, polishes, cleaning solvents, cosmetics, toiletries, etc.), shipping containers (for solvents, industrial adhesives, etc.) and vehicle fuel tanks produced within nominally conventional plastics processing equipment.

On an historical note, controlled surface fluorination of polymeric materials has been practised since the 1930s (see Ch. 4, p. 91) by workers wishing to passivate rubber gaskets, etc. to attack by elemental fluorine

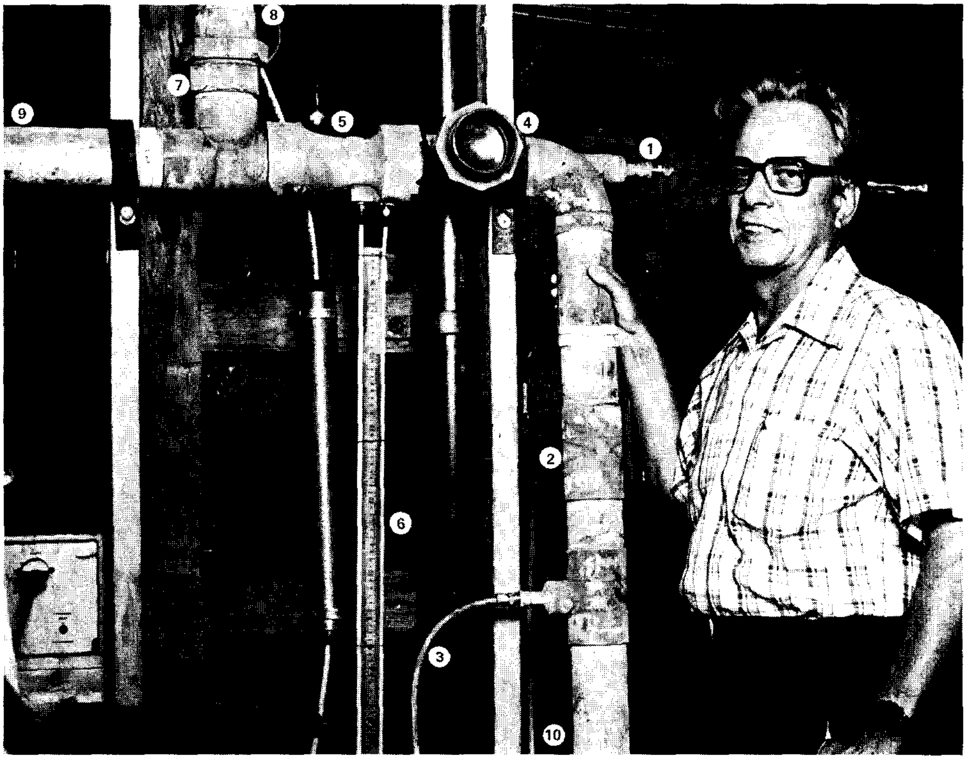

Fig. 11.2. Dr. Edward A. Tyczkowski (President, Armageddon Chemical Company, Durham, NC 27703, U.S.A.) with his jet fluorination reactor: ① organic feedstock inlet jet ② fluorine inlet (behind) ③ product exit line ④ fluoropolymer (Halar®) observation window ⑤ venturi tube ⑥ PTFE (Teflon®) manometer filled with chlorofluorocarbon oil ⑦, ⑧ PTFE rupture disc and vent, respectively ⑨ to main reaction zone and heat-exchanger ⑩ from heat-exchanger and blower.

[206]; and Rudge [207] invented a process in the early 1950s for converting thin (0.0076 cm) sheets of poly(ethylene) to perfluorinated material via treatment with fluorine, while Joffre [208] worked on the surface fluorination of film and bottles made from poly(ethylene).

Fluorination of carbon: commercial production of carbon tetrafluoride and graphite fluoride

The direct fluorination of carbon, first described by Moissan (see Chapter 4), has achieved commercial importance in two quite different directions: production of the simplest and most volatile fluorocarbon, CF_4 (see Appendix 11.11), and of graphite fluoride — a solid, layered, non-stoichiometric fluorocarbon of empirical formula CF_x, where $0 < x <$ *ca.* 1.25 [209].

Fluorine combines with graphite to yield three solid compounds, often referred to simply as carbon monofluoride, dicarbon monofluoride and tetracarbon monofluoride; the best known of these is the first, accurately named as poly(carbon monofluoride), $[CF]_n$, and produced by direct fluorination of graphite or other forms of carbon (*e.g.* petroleum coke, carbon black) under controlled conditions at temperatures in the range 400 - 600 °C. Material of composition $CF_{>1}$ is called superstoichiometric graphite fluoride and is snow-white in colour. Other grades vary from black ($x = 0.25$), through grey ($x = 0.9$) to ivory ($x = 1.0$). Full details of the history, preparation, properties, structures and commercial uses of graphite fluorides can be gained from a recent review [209]. The materials first became available in a recognisably commercial manner in 1970 when Meshri and White of the Ozark–Mahoning Company (U.S.A.) produced the first Fluorographite® polymers, composition $CF_{1.26}$; the range now comprises materials of composition $CF_{0.23}$ up to superstoichiometric [210]. Later, other companies in America and Japan (see Appendix 11.12) commenced production, and the current global use, mainly in CF_x/Li dry batteries and lubricants, is estimated to lie in the region of 150 000 lb per annum [210].

Defluorination of carbon monofluoride with powdered magnesium at 700 °C and 20 000 atm pressure yields a mixture of diamonds and fluorinated diamonds [211]. Moissan would have approved.

Fluorination using halogen fluorides

Usually, both halogens are introduced into the products [212] when these react with organic matter. Some are extremely reactive, and have been proposed as components of rocket fuels, propellants, *etc.* An interesting report has appeared of the rates of explosive reactions that can occur between chlorine trifluoride and organic substrates, even fluorocarbons [213].

Fluorination by high-valency metal fluorides

This technique was evolved during the Manhattan Project (see Chapter 5). As most often used, with cobalt(III) fluoride as the fluorinating agent, it is still the method of choice for synthesising fluorocarbons of medium molecular weights on large laboratory [214] or small industrial scales. As usually run, the organic feedstock is passed in vapour form over the solid fluorinating agent which is held in a simple stirred tubular reactor at temperatures around 350 °C. The spent fluorinating agent is then regenerated by elemental fluorine in a separate stage. The hydrocarbon feedstock meets progressively more depleted fluorinating agent as the run proceeds, so that conditions are not constant throughout:

$$\dashrightarrow CoF_2 \xrightarrow[350\ ^\circ C]{F_2} CoF_3 \xrightarrow[\text{feed}]{\text{organic}} \text{fluoro-organic product} + CoF_2 \dashrightarrow$$

In the industrial process however (see Appendix 11.13), fluorine and the organic feedstock are introduced simultaneously, and the bed of cobalt fluorides is fluidised so that much more uniform conditions are achieved [215].

The process has been employed for much fluorocarbon synthesis, but it has also been possible to run it at lower temperatures, so that some reactive centres remain in the fluorinated products. With hydrocarbon feedstocks, including arenes, very little unsaturated material is normally found amongst the products, which are largely polyfluorides, with a few hydrogens remaining. Benzene gave a mixture of polyfluorocyclohexanes, and the most significant reaction of these was with aqueous potash, loss of HF occurring to generate C=C bonds. Many polyfluorocyclohexanes and thence per- and poly-fluorocyclo-hexenes and -dienes were made thus [121, 216]. When the fluorocyclohexanes had 3 or 4 hydrogen substituents, hexa- and pentafluorobenzene, respectively, were formed, which permitted systematic investigation [121, 143] of the highly fluorinated arene series (see p. 455).

Per- and poly-fluorocyclopentadienes were made analogously [217]. The first synthesis of perfluorocyclopentadiene was from the perchloro analogue, by fluorine addition to the double bonds using CoF_3, followed by dechlorination with zinc [218]; extensive studies of the diene in reactions of the Diels–Alder type followed [219]. Fluorinations of bicyclic hydrocarbons gave good yields of the corresponding 1*H*-perfluorides, the hydrogens at the bridgehead positions resisting replacement; these products were of general synthetic value (see p. 445). Following the fluorination of cycloheptane by CoF_3, trideca- and dodeca-fluorocycloheptanes were isolated, and converted into undecafluorocycloheptene and decafluorocyclohepta-1,3- and -1,4-diene [220]. Synthetic sequences on the last two products allowed the first preparation [221] of perfluorocycloheptatriene $\overline{\mathrm{CF{=}CF{-}CF{=}CF{-}CF{=}CF{-}C}}\mathrm{F_2}$. Although CF_2 groups are normally very stable, the one present in this compound is so activated by the conjugated unsaturation that hydrolysis occurs, even by water alone or in moist air, to give [221] perfluorotropone $\overline{\mathrm{CF{=}CF{-}CF{=}CF{-}CF{=}CF{-}C}}\mathrm{{=}O}$.

The furan skeleton was preserved on fluorination by CoF_3, a range of polyfluoro-oxolans being obtained, from which per- and poly-fluorofurans were made by dehydrofluorination [222].

It has been found that complex fluorides based on CoF_3, *e.g.* $KCoF_4$ [223], offer useful variants in fluorinating activity. In particular, many more unsaturated products are formed; indeed using $CsCoF_4$, hexafluorobenzene was made directly from benzene [224]. The thiophene nucleus was degraded by CoF_3, but by use of $KCoF_4$, followed by dehydrofluorination, perfluorothiophen was isolated [225]. Nitriles and nitro compounds may be fluorinated by these reagents, with retention of the functional groups in the highly fluorinated products [226].

Fluorinations of diethyl and of ethyl methyl ethers at low temperatures gave families of polyfluoroethers [227], some of which had anaesthetic activities. Free-radical adducts of ethers to perfluoro-olefins have been fluorinated by CoF_3 at temperatures up to 400 °C; in many cases good yields of the corresponding perfluoroethers were obtained [228].

It has been suggested that the reaction mechanisms for all of these fluorinations by high-valency metal fluorides involve the initial oxidation of the substrate by the metal to give an intermediate radical-cation, which is then quenched by fluorine; the process is then repeated until high levels of fluorination are reached [229]. The fluorinating powers of the reagents seem to follow the oxidation potentials of the metal ions concerned, and the ease of oxidation of an organic substrate is related to its behaviour on fluorination. A similar mechanism can be applied to electrochemical fluorination (see p. 271).

Electrochemical fluorination (ECF)

This technique was the second great contribution[31] to organofluorine chemistry made by J. H. Simons. In principle, it is very simple; very many organic compounds dissolve readily in anhydrous HF, and the solutions will conduct electricity (if necessary, an additive can be used to increase conductivity). When current is passed at 4 - 8 V (usually 4.5 - 6 V), free fluorine is not evolved at the anode; however, hydrogen is given off at the cathode, and the organic substrate is per-fluorinated. First devised by Simons in 1941, publication was delayed until 1949 [231].

The process is usually run at 0 °C in a metal vessel fitted with a pack of metal plates as electrodes, alternately connected as anodes and cathodes; nickel is the preferred anode material (Fig. 11.5). Higher-boiling perfluorinated products are often immiscible with AHF, and can be run off from the bottom of the cell. The process has been described in Simons' own book [232], in others [94, 120] and in detail in reviews [127, 133, 233] where much of the earlier literature is cited.

The fluorination of hydrocarbons is not particularly easy, and the true value of electrochemical fluorination is that when certain functional groups are present in the starting materials, then they (or related reactive centres) can be retained in the perfluoro products. Some important examples are as follows: ethers → perfluoroethers; RCOF (or other carboxyl derivatives) → R_FCOF (long-chain acids also give cyclic perfluoroethers by ring-closures); $RSO_2F \rightarrow R_FSO_2F$; $RNH_2 \rightarrow R_FNF_2$; $R(R')NH \rightarrow R_F(R'_F)NF$; $R_3N \rightarrow (R_F)_3N$. Various oxygen- and nitrogen-containing heterocyclic compounds (also some containing both) are converted to their perfluoro analogues and C—S bonds can be preserved in organosulphides. The process provided the first practicable routes by direct fluorination to fluorocarbon derivatives possessing functional groups, on which synthetic chemistry could be performed. Its early successes included the production in good yields of trifluoroacetyl

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[31] See Chapter 4, p. 91 for the report on J. H. Simons' original fluorocarbon synthesis. Most of his researches into fluorine chemistry were done at Pennsylvania State University and at the University of Florida (Figs. 11.3 and 11.4). Appreciations by Dresdner [230] of his life (1897 - 1983) and work have just been published in a Memorial Issue of *J. Fluorine Chem.*, together with the address ("The Seven Ages of Fluorine Chemistry") that he gave on 19 July, 1973, when he received the Award of the Fluorine Division of the American Chemical Society for Creative Work in Fluorine Chemistry, sponsored by PCR Inc. Also included in the Issue are original papers on later developments in his process.

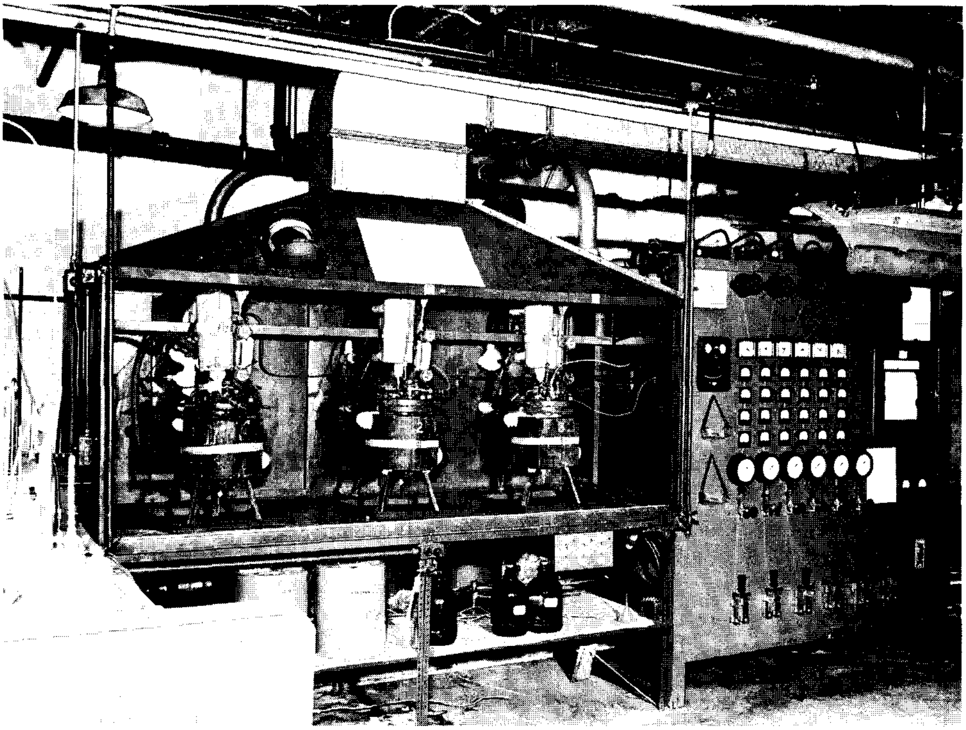

Fig. 11.3. Simons' ECF cells in the Fluorine Laboratories at Pennsylvania State University.

fluoride, and of trifluoromethanesulphonyl fluoride. The corresponding acids were thus made readily available, and they and their derivatives have found extensive use, not only in organofluorine chemistry, but also as reagents in general organic chemistry. Acid derivatives with longer chains are produced in lower yields, which however cannot usually be bettered by other routes. For laboratory work, the reaction is still run in much the same way; it is still utilised mainly to make perfluorinated compounds of the types indicated above. There have been few reports of its use for partial fluorination.

A later variant of the process [234] used an electrolyte of composition KF·2HF (approx.) and the electrolysis was conducted within the confines of a porous carbon anode; hydrocarbons and chlorohydrocarbons were fluorinated in this way. Papers in the Simons Memorial issue of *J. Fluorine Chem.* describe the use of porous or foam nickel anodes, and a close study of reaction variables, in the fluorinations of propene and octanoyl chloride (to give a mixture of $C_7F_{15}COF$, $\overline{\mathrm{OCF_2CF_2CF_2CF_2C}}\mathrm{FC_3F_7}$, $\overline{\mathrm{OCF_2CF_2CF_2C}}\mathrm{FC_4F_9}$ and C_7F_{16}) [235]; construction of cells based on advanced design criteria and controlled by microprocessors, their use being exemplified by the synthesis of $CF_2(SO_2F)_2$ [236]; synthesis of a large range of perfluorinated aminoalkyl ethers as candidate inert fluids [237].

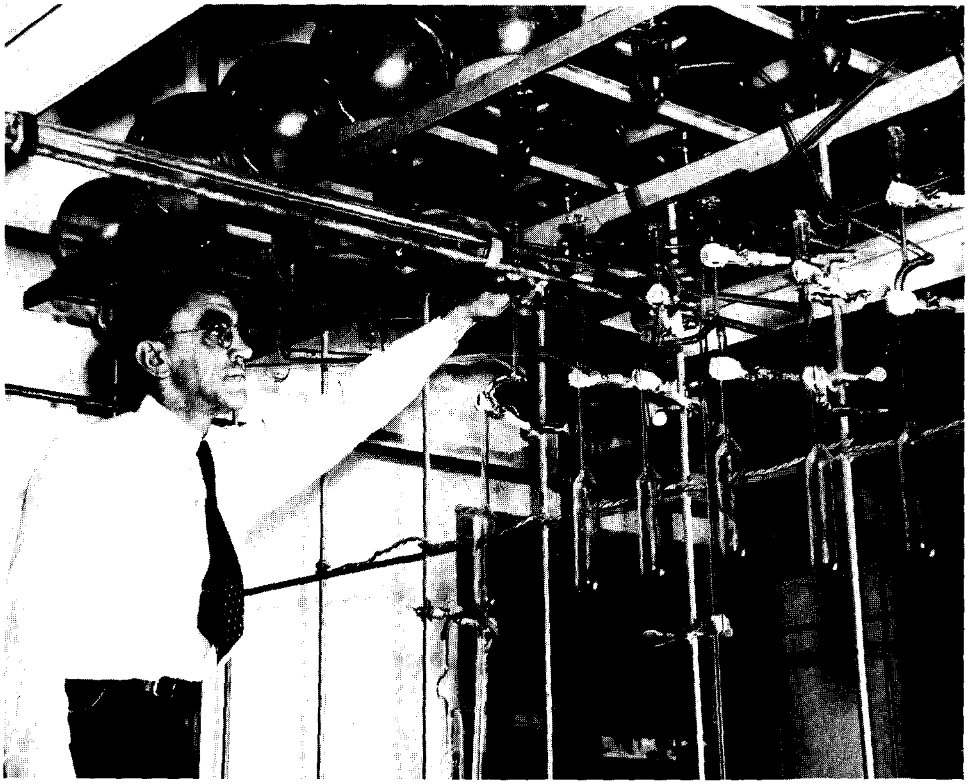

Fig. 11.4. Joe Simons at the University of Florida in the 1950s.

The mechanism of the electrochemical fluorination reaction has been the subject of much speculation (*cf.* refs. 127, 233). Evidence was recently adduced [238] in favour of a pathway of the radical-cation type. This was originally proposed for fluorinations by high-valency metal fluorides and extended to the electrochemical process [229]; such a mechanism seems to be the most favoured possibility at present [237].

Parallel with the establishment of the Simons process as a research tool, the 3M Company of St. Paul, Minnesota, carried out a vast programme of research and developmental work to create markets for the new fluorinated products. A fascinating account of this project has been provided by Pearlson [239]. The result is an impressive list of fluorine-containing products supplied by the company — around 250 now — the majority of which depend for their utility on the presence of a perfluoroaliphatic residue arising from the Simons electrofluorination process.

The major areas of application are as follows: (i) in surface treatments for fabrics, paper, leather, carpets, etc. to give resistance to oil, to water and to soiling (Fig. 11.6); (ii) in Light Water® foams used as fire-fighting chemicals; (iii) surfactant materials to reduce surface tension and create foam in aqueous and non-aqueous systems (one important example is in electro-

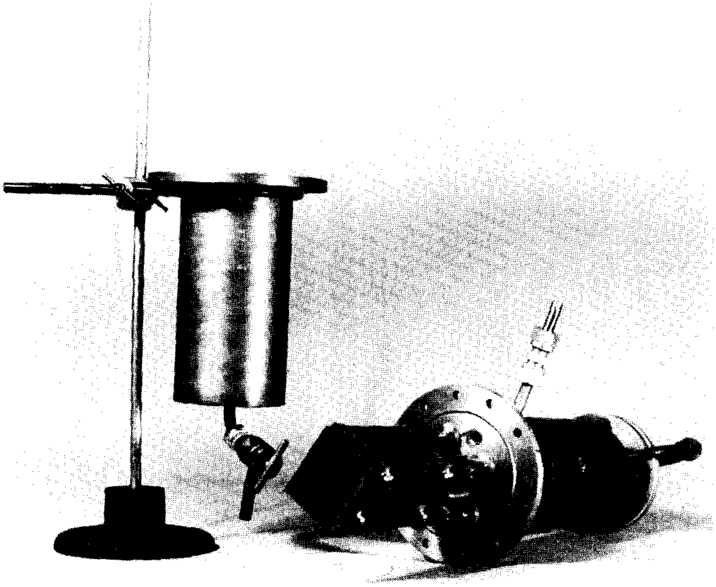

Fig. 11.5. U.M.I.S.T. one-litre all-nickel ECF cell.

plating baths); (iv) inert liquids for many uses, particularly testing media for electronic components, coolants in high-performance electronic systems and working fluids for vapour-phase soldering. A 3M fluid is one of the components of the artificial blood substitute Fluosol-DA (see Chapter 13).

In the earlier industrialisations of organofluorides (chlorofluorocarbons, the Manhattan Project), new materials were needed and compounds were found to satisfy the requirements. The commercialisation of these products by the 3M Company was different. Materials with entirely new properties were being made; it was necessary to go out and find markets where they could be exploited.

Commercial applications of organofluorine chemicals — some further observations

Adressing the 7th European Symposium on Fluorine Chemistry in Venice during September 1980, Lombardo [240] of Montedison's Industrial Products Division congratulated post-war fluorine chemists and technologists for having created "an industrial chemical activity which has withstood the oil crisis, inflation, and the chemical industry's loss of leadership. Few fluorine products have been in decline during the last five years". However losses on the organic side of the fluorochemicals industry had been fairly serious at one stage. This was due to the impact on chlorofluorocarbon

Fig. 11.6. Fluids resistance of fluorinated fabrics. (Photograph reproduced by permission of the Commercial Chemicals Division/3M, St. Paul, Minnesota, U.S.A.)

production of the much-publicised Rowland–Molina ozone-depletion hypothesis, advanced in 1974, and an on-going subject of discussion and concern [241] (see also Chapter 12). The measured ozone levels are not yet as seriously affected as the most alarmist predictions foretold however. Despite the enforced cutback in chlorofluorocarbon usage in aerosol propellants (mainly $CFCl_3$ and CF_2Cl_2), compounds of this class are finding increasing use [242] as refrigerants, solvents, foam-blowing agents and fire extinguishants (brominated compounds, *e.g.* CF_2ClBr, CF_2BrCF_2Br), etc. An ever-expanding market exists also for fluoropolymers and other entities based on olefins stemming from chlorofluorocarbons (*e.g.* $CHF_2Cl \rightarrow C_2F_4$; $CH_3CF_2Cl \rightarrow CH_2{=}CF_2$). Overall, in fact, the prospects for the organofluorine chemicals industry appear bright. Current research thrusts are particularly in the areas of agriculture, medicine and energy. Uses covered in recent reviews [241] include fluorinated dyes, surfactants, textile chemicals, plastics, elastomers, graphite, pesticides, drugs, anaesthetics, blood substitutes, X-ray contrast agents, fluids for the electronics and power industries, atmospheric tracers and explosives taggants, fire extinguishants, refrigerants, aerosol propellants and solvents.

Poly(tetrafluoroethylene) (PTFE), the first *fluorocarbon* to be commercialised (see Chapter 4), is still the main contributor to the growing

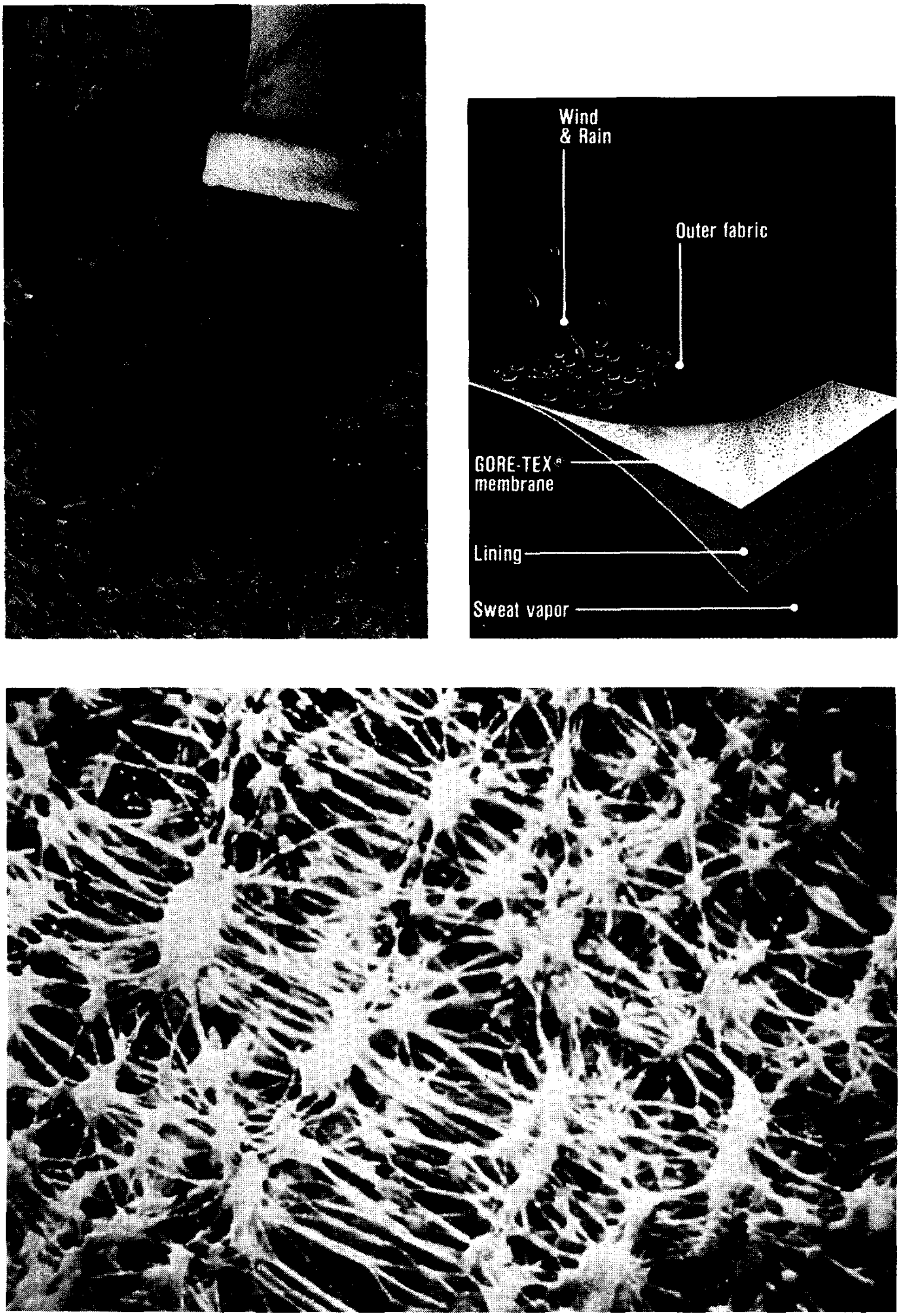

Fig. 11.7. *(For caption see opposite.)*

fluoropolymers market, which in 1985 was valued worldwide at \$1000 million per annum [243]. In general, fluoropolymers possess the now expected but still unique combinations of high thermal stability, chemical inertness, unusual surface properties, low dielectric constants and dissipation factors, low water absorptivities, excellent weatherability and low flammabilities. Therefore despite their relatively high costs (*e.g.* granular PTFE £7.45 per kg in 1985; *cf.* HDPE *ca.* £600 per tonne in mid-1985 [244], they often proved the cheapest method of carrying out a job. As maintenance costs rise, and equipment and control systems become more complex, the need to avoid down-time and malfunctions becomes more acute; safety and environmental factors, too, enter the costings. Clearly, the usage of speciality fluoropolymers — plastics, elastomers, greases and oils — which do not deteriorate, becomes increasingly justified by real economics.

Simons lived to see fluoropolymers make important contributions not only to conventional aviation but also to aerospace activities [245 - 249]; his particular concern about fire hazards (see p. 228) must certainly have caused him to note the use of PVF [poly(vinyl fluoride)] in the cabin furnishings area of civil aircraft [246, 248]. PTFE, of course, touches people's everyday lives in numerous ways, for example in the kitchen as non-stick linings for cooking pots and pans, in motor cars as gaskets and brake components, in the hospital as life-saving artificial body-part replacements, and in countless electrical appliances as insulators. Architects and engineers use glass fabric coated with the Du Pont 'Teflon' fluorocarbon resin as an architectural fabric. The coated glass fabric withstands the elements, meets modern building codes, is flame resistant and translucent. The Pontiac Silverdome, home of the NFL's Detroit Lions, is a 10-acre glass fabric dome roof covered with 'Teflon'. A further use is in weatherproof footwear and clothing (Fig. 11.7).

PTFE and other fluorinated polymers are also used to protect from moisture optical fibres fabricated from *fluoride glasses* (*e.g.* BZLA made

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Fig. 11.7. Women's fashion boots incorporating Gore-Tex® fabric as a waterproof barrier (left) (® registered trademark of W. L. Gore & Associates, Inc., Maryland, U.S.A.). Introduced commercially in 1976, Gore-Tex® fabrics are made by laminating an *expanded* poly(tetrafluoroethylene) film to a nylon or other fabric base (right); they keep out rain and chilling wind, yet allow body perspiration to escape.

A Gore-Tex® membrane (centre, magnification 5000×) has 9 billion tiny pores per square inch, each being 700 times larger than a water molecule but thousands of times smaller than a drop of liquid water; hence it is both waterproof *and* 'breathes'. Since the membrane's pores are so small and are also misaligned, Gore-Tex® fabric is windproof, keeping wearers much warmer than conventional fabrics can. Rainwear, ski clothes, running suits, shoes and other outdoor apparel incorporating Gore-Tex® fabrics are well known nowadays; military applications are growing, particularly following the use of foulweather gear by British troops in the 1982 Falklands campaign. Amongst a myriad of other uses, Gore-Tex® expanded PTFE finds important medical uses in the form of an assortment of body implant devices; natural tissue grows into the open pores and thereby prevents rejection by the immune system. (Photographs reproduced by permission of W. L. Gore & Associates, Inc.)

from BaF_2, ZrF_4, LaF_3 and AlF_3), which are potentially a hundred times more transparent than oxide glasses. Still in the research and development stage, such fibres — when available to telecommunications engineers — will provide a choice for global communications between radio links via satellite and optical links via cable [250].

Fluorine chemistry — both organic and inorganic, academic and industrial — continues to enjoy a growth situation. May the next 100-year period be as fruitful as the first one.

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References

1 J. H. Simons, *Ind. Eng. Chem., 39* (1947) 238.
2 E. T. McBee, *Ind. Eng. Chem., 39* (1947) 236.
3 A. V. Grosse and G. H. Cady, *Ind. Eng. Chem., 39* (1947) 367.
4 J. H. Simons, *Chem. Eng. (N.Y.), 57* (1950) 129.
5 See J. D. Park, in J. H. Simons (ed.), *Fluorine Chemistry*, Vol. I, Academic, New York, 1950, p. 523 for a review of early work on aliphatic chlorofluoro compounds.
6 J. D. Park, A. F. Benning, F. B. Downing, J. F. Laucius and R. C. McHarness, *Ind. Eng. Chem., 39* (1947) 354.
7 J. Harmon, *U.S. Pat. 2 404 374* (1946) *(Chem. Abs., 40* (1946) 7234^3).
8 W. E. Hanford and G. W. Rigby, *U.S. Pat. 2 409 274* (1946) *(Chem. Abs., 41* (1947) 982b).
9 A. L. Henne and P. Trott, *J. Am. Chem. Soc., 69* (1947) 1820.
10 A. L. Henne and T. H. Newby, *J. Am. Chem. Soc., 70* (1948) 130.
11 E. T. McBee, P. A. Wiseman and G. B. Bachman, *Ind. Eng. Chem., 39* (1947) 415.
12 A. L. Henne and R. P. Ruh, *J. Am. Chem. Soc., 69* (1947) 279.
13 J. A. Young, *J. Chem. Educ., 47* (1970) 733.
14 I. L. Knunyants, *Izv. Akad. Nauk. SSSR, Ser. Khim.,* (1974) 1098.
15 D. E. M. Evans and J. C. Tatlow, *J. Chem. Soc.,* (1955) 1184; *idem*, in D. H. Desty and C. L. A. Harbourn (eds.), *Vapour Phase Chromatography*, Butterworths London, 1956, p. 256; R. E. Banks, *Ph.D. Thesis*, University of Durham, 1956.
16 H. G. McDonnell, *Int. Lab.,* (October 1980) 57.
17 D. G. Weiblen, in J. H. Simons (ed.), *Fluorine Chemistry*, Vol. II, Academic, New York, 1954, p. 449.
18 J. K. Brown and K. J. Morgan, *Adv. Fluorine Chem., 4* (1965) 253. (See also, P. M. Treichel and F. G. A. Stone, *Adv. Organomet. Chem., 1* (1964) 212 for a discussion of the infrared spectra of some fluorocarbon–metal compounds.)

19 J. R. Majer, *Adv. Fluorine Chem.*, *2* (1961) 55.

20 See, for example, R. E. Banks and H. Goldwhite, in F. A. Smith (ed.), *Handbook of Experimental Pharmacology*, Vol. XX, *Pharmacology of Fluorides (Part I)*, Springer Verlag, Berlin, 1966, p. 1; C. M. Sharts and W. A. Sheppard, *Org. React.*, *21* (1974) 125; M. R. C. Gerstenberger and A. Haas, *Angew. Chem.*, *Int. Ed. Engl.*, *20* (1981) 647; M. Hudlicky and T. Hudlicky, in S. Patai and Z. Rappoport (eds.), *The Chemistry of Functional Groups*, Suppl. D, *The Chemistry of Halides, Pseudohalides and Azides, Part 2*, Wiley-Interscience, Chichester, 1983, p. 1022; A. Haas and M. Lieb, *Chimia*, *39* (1985) 134.

21 W. Smith, *Angew. Chem., Int. Ed. Engl.*, *1* (1962) 467; G. A. Boswell, W. C. Ripka, R. M. Scribner and C. W. Tullock, *Org. React.*, *21* (1974) 1; C.-L. J. Wang, *Org. React.*, *34* (1985) 319.

22 W. J. Middleton and E. M. Bingham, *Org. Synth.*, *57* (1977) 50.

23 W. J. Middleton, *J. Org. Chem.*, *40* (1975) 574; L. N. Markovsku, V. E. Pashinnik and A. V. Kirsanov, *Synthesis*, (1973) 787.

24 J. Cochran, *Chem. Eng. News*, *57* (March 19, 1979) 4, 74; R. J. Breckenbridge, W. J. S. Lyall and C. J. Suckling, *Chem. Br.*, *18* (1982) 619.

25 W. J. Middleton, *Chem. Eng. News*, *57* (May 21, 1979) 43.

26 W. J. Middleton, *U.S. Pat. 3 940 402* (1976) (*Chem. Abs.*, *85* (1976) 6388j).

27 W. B. Farnham and R. L. Harlow, *J. Am. Chem. Soc.*, *103* (1981) 4608.

28 O. W. Webster, W. R. Hertler, D. Y. Sogah, W. B. Farnham and T. RajanBabu, *J. Am. Chem. Soc.*, *105* (1983) 5706.

29 W. A. Szarek, G. W. Hay and B. Doboszewski, *J. Chem. Soc., Chem. Commun.*, (1985) 663.

30 R. Noyori, I. Nishida and J. Sakata, *J. Am. Chem. Soc.*, *105* (1983) 1598; T. V. RajanBabu and T. Fukunaga, *J. Org. Chem.*, *49* (1984) 4571; M. Fujita and T. Hiyama, *J. Am. Chem. Soc.*, *107* (1985) 4085.

31 G. G. Yakobson and N. E. Akhmetova, *Synthesis*, (1983) 169.

32 J. H. Clark, *Chem. Rev.*, *80* (1980) 429.

33 G. A. Olah, G. K. S. Prakash and J. Sommer, *Superacids*, Wiley-Interscience, New York, 1985.

34 *Chem. Ind. (London)*, (1983) 651; T. C. Stening, C. P. Smith and P. J. Kimber, *Mod. Plast. Int.*, (March 1982) 55; H. R. Kricheldorf and G. Bier, *Polymer*, *25* (1984) 1151 and references therein; *U.S. Pats. 4 105 636* (1978) and *4 331 798* (1978) (to I.C.I.).

35 W. J. Feast and J. N. Winter, *J. Chem. Soc., Chem. Commun.*, (1985) 202.

36 R. S. Liu and C. G. Krespan, *J. Org. Chem.*, *34* (1969) 1271.

37 D. M. Lemal and L. H. Dunlap, *J. Am. Chem. Soc.*, *94* (1972) 6562.

38 See, for example, C. R. Brundle, M. B. Robin, N. A. Kuebler and H. Basch, *J. Am. Chem. Soc.*, *94* (1972) 1451; C. R. Brundle, M. B. Robin and N. A. Kuebler, *ibid.*, *94* (1972) 1466; D. M. Kanjia, J. Mason, I. A. Stenhouse, R. E. Banks and N. D. Venayak, *J. Chem. Soc., Perkin Trans. 2*, (1981) 975.

39 A. Greenberg, J. F. Liebman and D. van Vechten, *Tetrahedron*, *36* (1980) 1161.

40 B. E. Smart, in S. Patai and Z. Rappoport (eds.), *The Chemistry of Functional Groups*, Suppl. D, *The Chemistry of Halides, Pseudohalides and Azides, Part 1*, Wiley-Interscience, Chichester, 1983, p. 603.

41 P. L. Coe, A. Sellars, J. C. Tatlow, G. Whittaker and H. C. Fielding, *J. Chem. Soc., Chem. Commun.*, (1982) 362.

42 J. L. Hencher, Q. Shen and D. G. Tuck, *J. Am. Chem. Soc.*, *98* (1976) 899.

43 Y. Kobayashi, A. Ando, K. Kawada and I. Kumadaki, *J. Org. Chem.*, *45* (1980) 2966, 2968.

44 M. G. Barlow, R. N. Haszeldine and J. G. Dingwall, *J. Chem. Soc., Perkin Trans. 1*, (1973) 1542.

45 W. J. Middleton, *J. Org. Chem.*, *34* (1969) 3201.

46 D. Wirth and D. M. Lemal, *J. Am. Chem. Soc.*, *104* (1982) 847.

47 G. Pitt, R. A. Russell and R. N. Warrener, *J. Chem. Soc., Chem. Commun.*, (1984) 1466.
48 For a review, see W. H. Sharkey, *Fluorine Chem. Rev.*, *2* (1968) 1.
49 S. Cohen, J. R. Lacher and J. D. Park, *J. Am. Chem. Soc.*, *81* (1959) 3480.
50 J. D. Park, M. L. Sharrah and J. R. Lacher, *J. Am. Chem. Soc.*, *71* (1949) 2337; J. D. Park, C. M. Snow and J. R. Lacher, *ibid.*, *73* (1951) 2342.
51 R. West (ed.), *Oxocarbons*, Academic, New York, 1980.
52 A. F. Benning, F. B. Downing and J. D. Park, *U.S. Pat. 2 394 581* (1946) *(Chem. Abs.*, *40* (1946) 3460^6).
53 E. E. Lewis and M. A. Naylor, *J. Am. Chem. Soc.*, *69* (1947) 1968; R. J. Hundai and K. Baum, *Synthesis*, (1982) 454.
54 A. T. Morse, P. B. Ayscough and L. C. Leitch, *Can. J. Chem.*, *33* (1955) 453.
55 E. W. Cook and J. S. Pierce, *Nature (London)*, *242* (1973) 337.
56 D. W. Roberts, *Tetrahedron*, *41* (1985) 5529.
57 P. D. Bartlett, L. K. Montgomery and B. Seidel, *J. Am. Chem. Soc.*, *86* (1964) 616; L. K. Montgomery, K. Schueller and P. D. Bartlett, *ibid.*, *86* (1964) 622; P. D. Bartlett and L. K. Montgomery, *ibid.*, *86* (1964) 628; P. D. Bartlett, *Q. Rev. Chem. Soc.*, *24* (1970) 473.
58 R. Hoffman and R. B. Woodward, *J. Am. Chem. Soc.*, *87* (1965) 2048.
59 See, for example, J. M. Tedder and J. C. Walton, *Acc. Chem. Res.*, *9* (1976) 183; *idem*, *Tetrahedron*, *36* (1980) 701.
60 For reviews of electrophilic attack on fluoro-olefins, see B. L. Dyatkin, E. P. Mochalina and I. L. Knunyants, *Russ. Chem. Rev.*, *35* (1966) 417 and *Fluorine Chem. Rev.*, *3* (1969) 45; L. S. German and I. L. Knunyants, *Angew. Chem., Int. Ed. Engl.*, *8* (1969) 349.
61 P. G. Gassman and T. T. Tidwell, *Acc. Chem. Res.*, *16* (1983) 279.
62 T. T. Tidwell, *Angew. Chem., Int. Ed. Engl.*, *23* (1984) 20.
63 G. A. Olah, R. D. Chambers and M. B. Comisarow, *J. Am. Chem. Soc.*, *89* (1967) 1268.
64 For a review of fluorinated carbocations, see G. A. Olah and Y. K. Mo, *Adv. Fluorine Chem.*, *7* (1973) 69.
65 G. Modena and G. Scorrano, in S. Patai (ed.), *The Chemistry of the Carbon–Halogen Bond, Part 1*, Wiley-Interscience, London, 1973, p. 301.
66 G. Baddeley, *J. Chem. Soc.*, (1950) 663.
67 D. T. Clark, J. N. Murrell and J. M. Tedder, *J. Chem. Soc.*, (1963) 1250.
68 P. Politzer and J. W. Timberlake, *J. Org. Chem.*, *37* (1972) 3557.
69 R. Bolton and J. P. B. Sandall, *J. Chem. Soc., Perkin Trans. II*, (1976) 1541.
70 A. R. Katritzky and R. D. Topsom, *J. Chem. Educ.*, *48* (1971) 427 (a review of σ- and π-inductive effects).
71 J. Burdon, *Tetrahedron*, *21* (1965) 3373.
72 E. Nield, R. Stephens and J. C. Tatlow, *J. Chem. Soc.*, (1959) 166.
73 P. C. Myhre and G. D. Andrews, *J. Am. Chem. Soc.*, *92* (1970) 7595, 7596.
74 P. B. Sargeant and C. G. Krespan, *J. Am. Chem. Soc.*, *91* (1969) 415.
75 W. P. Dailey and D. M. Lemal, *J. Am. Chem. Soc.*, *106* (1984) 1169.
76 F. T. Prochaska and L. Andrews, *J. Am. Chem. Soc.*, *100* (1978) 2102.
77 L. Andrews and F. T. Prochaska, *J. Chem. Phys.*, *70* (1979) 4714.
78 R. J. Flint, T. B. McMahon and J. L. Beauchamp, *J. Am. Chem. Soc.*, *96* (1974) 1269.
79 See ref. 40 and publications listed therein.
80 J. M. Birchall, R. Fields, R. N. Haszeldine and N. T. Kendall, *J. Chem. Soc., Perkin Trans. 1*, (1973) 1773.
81 For a review, see R. D. Chambers and R. H. Mobbs, *Adv. Fluorine Chem.*, *4* (1965) 50.
82 (a) W. T. Miller, J. H. Fried and H. Goldwhite, *J. Am. Chem. Soc.*, *82* (1960) 3091.
(b) W. T. Miller, W. Frass and P. R. Resnick, *J. Am. Chem. Soc.*, *83* (1961) 1767.

(c) For Bill Miller's own account of his work on the occasion of his 70th birthday, see *J. Fluorine Chem.*, *18* (1981) 305.
83 R. D. Chambers, R. A. Storey and W. K. R. Musgrave, *Chem. Commun.*, (1966) 384.
84 W. Dmowski and A. Haas, *Chimia, 39* (1985) 185 *(Chem. Abs.*, *104* (1986) 33 982r).
85 A. E. Bayliff, M. R. Bryce, R. D. Chambers and R. S. Matthews, *J. Chem. Soc., Chem. Commun.*, (1985) 1018.
86 See, for example, A. R. Bailey and R. E. Banks, *J. Fluorine Chem.*, *23* (1983) 87.
87 See S. Smith, in R. E. Banks (ed.), *Preparation, Properties, and Industrial Applications of Organofluorine Compounds*, Ellis Horwood, Chichester, 1982, p. 235, and references cited therein.
88 K. Seppelt, *Angew. Chem., Int. Ed. Engl.*, *16* (1977) 322; G. Klöter, W. Lutz, K. Seppelt and W. Sundermeyer, *ibid.*, *16* (1977) 707; G. Klöter and K. Seppelt, *J. Am. Chem. Soc.*, *101* (1979) 347.
89 S. Andreades, *J. Am. Chem. Soc.*, *86* (1964) 2003; see also the reviews by D. Holtz, *Progr. Phys. Org. Chem.*, *8* (1971) 1 and *Chem. Rev.*, *71* (1971) 139.
90 J. H. Sleigh, R. Stephens and J. C. Tatlow, *J. Fluorine Chem.*, *15* (1980) 411.
91 See, for example, P. von R. Schleyer and A. J. Kos, *Tetrahedron, 39* (1983) 1141.
92 W. B. Farnham, B. E. Smart, W. J. Middleton, J. C. Calabrese and D. A. Dixon, *J. Am. Chem. Soc.*, *107* (1985) 4565.
93 J. N. Murrell, S. F. A. Kettle and J. M. Tedder, *Valence Theory*, Wiley, New York, 1965, p. 309.
94 R. D. Chambers, *Fluorine in Organic Chemistry*, Wiley-Interscience, New York, 1973.
95 A. Streitwieser, D. Holtz, G. R. Ziegler, J. O. Stoffer, M. L. Brokaw and F. Guibé, *J. Am. Chem. Soc.*, *98* (1976) 5229.
96 K. J. Klabunde and D. J. Burton, *J. Am. Chem. Soc.*, *94* (1972) 5985.
97 A. Streitwieser and F. Mares, *J. Am. Chem. Soc.*, *90* (1968) 2444.
98 G. Baddeley, G. M. Bennett, S. Glasstone and B. Jones, *J. Chem. Soc.*, (1935) 1827.
99 See refs. 40, 65 and 71, and J. Burdon, D. W. Davies and G. del Conde, *J. Chem. Soc., Perkin Trans. 2*, (1979) 1205, and references cited therein.
100 O. A. Reutov, I. P. Beletskaya and K. P. Butin, in T. R. Crompton, (transl. ed.), *CH-Acids*, Pergamon, Oxford, 1978.
101 J. P. Lorand, J. Urban, J. Overs and Q. A. Ahmed, *J. Org. Chem.*, *34* (1969) 4176.
102 G. Paprott and K. Seppelt, *J. Am. Chem. Soc.*, *106* (1984) 4060. (See also G. Paprott, D. Lentz and K. Seppelt, *Chem. Ber.*, *117* (1984) 1153.)
103 E. D. Laganis and D. M. Lemal, *J. Am. Chem. Soc.*, *102* (1980) 6633.
104 D. W. Wiley, *U.S. Pat. 2 988 537* (1961) (to Du Pont).
105 C. G. Krespan, F. A. Van-Catledge and B. E. Smart, *J. Am. Chem. Soc.*, *106* (1984) 5544.
106 B. L. Dyatkin, L. G. Zhuravkova, B. I. Martynov, S. R. Sterlin and I. L. Knunyants, *J. Chem. Soc., Chem. Commun.*, (1972) 618.
107 D. C. England and C. G. Krespan, *J. Am. Chem. Soc.*, *88* (1966) 5582. For a review of fluoroketene chemistry, see Yu. A. Cheburkov and I. L. Knunyants, *Fluorine Chem. Rev.*, *1* (1967) 107.
108 H. Millauer, W. Schwertfeger and G. Siegemund, *Angew. Chem., Int. Ed. Engl.*, *24* (1985) 161.
109 R. E. Banks and G. J. Moore, *J. Chem. Soc. (C)*, (1966) 2304.
110 For the first report on this now very well investigated type of reaction, see W. J. Brehm, K. G. Bremer, H. S. Eleuterio and R. W. Meschke, *U.S. Pat. 2 918 501* (1959) (to Du Pont).
111 See, for example, R. E. Banks and P. J. King, 'Chemistry and Physics of Petroleum', in G. D. Hobson (ed.), *Modern Petroleum Technology*, 5th Ed., Part I, Wiley, Chichester, 1984, p. 279.
112 H. C. Fielding and A. J. Rudge, *Br. Pat. 1 082 127* (1967) (to I.C.I.); W. R. Deem, *Br. Pat. 1 302 350* (1973) (to I.C.I.). See also D. P. Graham, *J. Org. Chem.*, *31* (1966) 955.

113 (a) R. E. Banks, K. Mullen, W. J. Nicholson, C. Oppenheim and A. Prakash, *J. Chem. Soc., Perkin Trans. 1*, (1972) 1098; R. E. Banks and C. Oppenheim, *J. Fluorine Chem.*, *12* (1978) 27; R. E. Banks and A. R. Bailey, *J. Fluorine Chem.*, *24* (1984) 117.
(b) A. R. Bailey, R. E. Banks, M. G. Barlow and M. Nickkho-Amiry, *J. Fluorine Chem.*, *15* (1980) 289.

114 (a) D. Collins, R. Stephens and J. C. Tatlow, *J. Fluorine Chem.*, *32* (1986) 213.
(b) S. F. Campbell, R. Stephens and J. C. Tatlow, *Chem. Commun.*, (1967) 151.
(c) S. F. Campbell, J. M. Leach, R. Stephens and J. C. Tatlow, *J. Fluorine Chem.*,*1* (1971/72) 85.
(d) J. Battersby, R. Stephens, J. C. Tatlow and L. F. Thomas, *J. Fluorine Chem.*, *15* (1980) 139.

115 (a) D. L. Beveridge, P. A. Dobosh and J. A. Pople, *J. Chem. Phys.*, *48* (1968) 4802.
(b) R. W. Fessenden and R. H. Schuler, *J. Chem. Phys.*, *43* (1965) 2704.
(c) L. D. Kispert, H. Liu and C. U. Pittman, *J. Am. Chem. Soc.*, *95* (1973) 1657.

116 K. V. Scherer, T. Ono, K. Yamanouchi, R. Fernandez, P. Henderson and H. Goldwhite, *J. Am. Chem. Soc.*, *107* (1985) 718.

117 W. H. Dawson, D. H. Hunter and C. J. Willis, *J. Chem. Soc., Chem. Commun.*, (1980) 874.

118 A. Bondi, *J. Phys. Chem.*, *68* (1964) 441.

119 C. R. Patrick, *Adv. Fluorine Chem.*, *2* (1961) 1.

120 R. E. Banks, *Fluorocarbons and Their Derivatives*, 2nd Ed., Macdonald, London, 1970.

121 J. C. Tatlow, in R. E. Banks (ed.), *Organofluorine Chemicals and Their Industrial Applications*, Ellis Horwood, Chichester, 1979, p. 19.

122 A. G. Sharp, *Q. Rev. Chem. Soc.*, *11* (1957) 49; *idem*, in *Carbon–Fluorine Compounds: Chemistry, Biochemistry and Biological Activities*, Elsevier, Amsterdam, 1972, p. 33.

123 J. Banus, H. J. Emeléus and R. N. Haszeldine, *J. Chem. Soc.*, (1951) 60.

124 J. H. Simons, *Fluorine Chem.*, *I* (1950) 404.

125 R. T. Sanderson, *Chemical Periodicity*, Reinhold, New York, 1960, pp. 53, 233.

126 A. A. Banks, A. Campbell and A. J. Rudge, *Nature (London)*, *174* (1954) 885.

127 A. J. Rudge, in A. T. Kuhn (ed.), *Industrial Electrochemical Processes*, Elsevier, Amsterdam, 1971, p. 1.

128 See, for example, D. S. L. Slinn and S. W. Green, 'Fluorocarbon Fluids for Use in the Electronics Industry', in R. E. Banks (ed.), *Preparation, Properties, and Industrial Applications of Organofluorine Compounds*, Ellis Horwood, Chichester, 1982, p. 45.

129 B. Gething, C. R. Patrick, J. C. Tatlow, R. E. Banks, A. K. Barbour and A. E. Tipping, *Nature (London)*, *183* (1959) 586; A. K. Barbour, *Chem. Br.*, *5* (1969) 260.

130 (a) See, for example, ref. 120 and reviews quoted therein.
(b) R. E. Banks and M. G. Barlow (Senior Reporters), *Fluorocarbon and Related Chemistry*, Vols. 1 - 3, The Chemical Society, London, 1971, 1974 and 1976.
(c) R. J. Lagow and J. A. Morrison, *Adv. Inorg. Chem. Radiochem.*, *23* (1980) 177; and J. A. Morrison, *ibid.*, *27* (1983) 293.

131 A. A. Banks, H. J. Emeléus, R. N. Haszeldine and V. Kerrigan, *J. Chem. Soc.*, (1948) 2188; H. J. Emeléus and R. N. Haszeldine, *ibid.*, (1949) 2948.

132 T. H. Coffield, J. Kozikowski and R. D. Classon, *Abstr. 5th Int. Conf. Coord. Chem. (London)*, (1959) 126.

133 T. Abe and S. Nagase, in R. E. Banks (ed.), *Preparation, Properties and Industrial Applications of Organofluorine Compounds*, Ellis Horwood, Chichester, 1982, p. 19.

134 A. L. Henne and W. G. Finnegan, *J. Am. Chem. Soc.*, *72* (1950) 3806; R. N. Haszeldine, *Nature (London)*, *166* (1950) 192; *idem*, *J. Chem. Soc.*, (1951) 584.

135 R. D. Chambers, W. K. R. Musgrave and J. Savory, *J. Chem. Soc.*, (1961) 3779; M. Hauptschein and M. Braid, *J. Am. Chem. Soc.*, *83* (1961) 2383.

136 R. N. Haszeldine, *J. Chem. Soc.*, (1949) 2856; *ibid.*, (1953) 3761.

137 T. Umemoto, Y. Kuriu, H. Shuyama, O. MiYano and S.-I. Nakayama, *J. Fluorine Chem.*, *20* (1982) 695; *ibid.*, *31* (1986) 37.

138 T. Umemoto and Y. Kuriu, *Chem. Lett.*, (1982) 65.

139 T. Umemoto, Y. Kuriu and H. Shuyama, *Chem. Lett.*, (1981) 1663.

140 T. Umemoto, *Tetrahedron Lett.*, *25* (1984) 81 (this paper contains numerous back references to the use of FITS reagents).

141 (a) W. Grot, *Chem. Ind. (London)*, (1985) 647.
(b) M. Seko, *Br. Pats. 1 497 748* (1978) and *1 497 749* (1978) (to Asahi Chemical Industry Co.).

142 (a) E. T. McBee, V. V. Lindgren and W. B. Ligett, *Ind. Eng. Chem.*, *39* (1947) 378.
(b) Y. Desirant, *Bull. Soc. Chim. Belg.*, *67* (1958) 676.

143 J. C. Tatlow, *Endeavour*, *22* (1963) 89.

144 L. A. Wall, W. J. Pummer, J. E. Fearn and J. M. Antonucci, *J. Res. Nat. Bur. Stand.*, *67A* (1963) 481.

145 R. E. Banks, A. E. Ginsberg and R. N. Haszeldine, *J. Chem. Soc.*, (1961) 1740; R. D. Chambers, J. Hutchinson and W. K. R. Musgrave, *J. Chem. Soc.*, (1964) 3573; R. E. Banks, R. N. Haszeldine, J. V. Latham and I. M. Young, *J. Chem. Soc.*, (1965) 594; for reviews see G. G. Yakobson, T. D. Petrova and L. S. Kobrina, *Fluorine Chem. Rev.*, *7* (1974) 115; R. D. Chambers and C. R. Sargent, *Adv. Heterocyclic Chem.*, *28* (1981) 1.

146 See the Memorial Issue of *J. Fluorine Chem.*, devoted to work by him and his group; *28* (1985) 1- 137.

147 G. Camaggi, F. Gozzo and Gb. Cevidalli, *Chem. Commun.*, (1966) 313; I. Haller, *J. Am. Chem. Soc.*, *88* (1966) 2070; G. Camaggi and F. Gozzo, *J. Chem. Soc. (C)*, (1969) 489.

148 W. Prescott, *Chem. Ind. (London)*, (1978) 56.

149 (a) M. Jarman and R. McCague, *J. Chem. Soc., Chem. Commun.*, (1984) 125; *J. Chem. Res. (S)*, (1985) 114.
(b) L. Kisfaludy and I. Schön, *Synthesis*, (1983) 325; E. Atherton and R. C. Sheppard, *J. Chem. Soc., Chem. Commun.*, (1985) 165.

150 Various authors, in R. E. Banks (ed.), *Organofluorine Chemicals and Their Industrial Applications*, Ellis Horwood, Chichester, 1979; L. Dolby-Glover, *Speciality Chemicals*, *5* (1985) 4 - 6, 8.

151 T. Haga, K. Fujikawa, T. Koyanagi, T. Nakajima and K. Hayashi, *Heterocycles*, *22* (1984) 117.

152 *Chem. Eng. News*, (September 23, 1985) 43.

153 (a) H. Schmand (of Riedel–de Haën AG, West Germany), "Diazofluorination of Aromatic Amines", *S.C.I. Symp. Fluoro-organic Compounds in Industry, London*, (1986); see also the impressive *Fluoroaromatics Catalogue (F)* issued by Riedel–de Haën AG recently.
(b) J. P. Regan (of Wendstone Chemicals, U.K.), "Use of the Balz–Schiemann Reaction", *S.C.I. Symp. Fluoro-organic Compounds in Industry, London*, (1986).

154 A. Haas and M. Lieb, *Chimia*, *39* (1985) 134.

155 E. H. Appelman, L. J. Basile and R. C. Thompson, *J. Am. Chem. Soc.*, *101* (1979) 3384. See also R. C. Thompson and E. H. Appelman, *Inorg. Chem.*, *19* (1980) 3248.

156 S. Stavber and M. Zupan, *J. Chem. Soc., Chem. Commun.*, (1981) 148.

157 S. Stavber and M. Zupan, *J. Fluorine Chem.*, *17* (1981) 597.

158 D. P. Ip, C. D. Arthur, R. E. Winans and E. H. Appelman, *J. Am. Chem. Soc.*, *103* (1981) 1964. See also E. H. Appelman, L. J. Basile and R. Hayatsu, *Tetrahedron*, *40* (1984) 189.

159 S. Stavber and M. Zupan, *J. Chem. Soc., Chem. Commun.*, (1981) 795.

160 E. H. Appelman, M. H. Mendelsohn and H. Kim, *J. Am. Chem. Soc.*, *107* (1985) 6515.

161 S. Rozen, O. Lerman and M. Kol, *J. Chem. Soc., Chem. Commun.*, (1981) 443; S. Rozen, O. Lerman, M. Kol and D. Hebel, *J. Org. Chem.*, *50* (1985) 4753; D. Hebel, O. Lerman and S. Rozen, *J. Fluorine Chem.*, *30* (1985) 141.

162 O. Lerman, Y. Tor, D. Hebel and S. Rozen, *J. Org. Chem.*, *49* (1984) 806.

163 S. Rozen and R. Filler, *Tetrahedron, 41* (1985) 1111 (*Tetrahedron Report No. 182*: "α-Fluorocarbonyl Compounds and Related Chemistry").

164 G. W. M. Visser, B. W. V. Halteren, J. D. M. Herschied, G. A. Brinkman and A. Hoekstra, *J. Chem. Soc., Chem. Commun.*, (1984) 655.

165 E. M. Kosower, D. Hebel, S. Rozen and A. E. Radkowski, *J. Org. Chem.*, *50* (1985) 4152.

166 C. M. Sharts and W. A. Sheppard, *Org. React.*, *21* (1974) 225.

167 D. H. R. Barton, *Pure Appl. Chem.*, *21* (1970) 285.

168 W. E. Barnette, R. C. Wheland, W. J. Middleton and S. Rozen, *J. Org. Chem.*, *50* (1985) 3698.

169 D. H. R. Barton, A. K. Ganguly, R. H. Hesse, S. N. Loo and M. M. Pechet, *Chem. Commun.*, (1968) 806.

170 M. J. Fifolt, R. T. Olczak and R. Mundhenke, *J. Org. Chem.*, *50* (1985) 4576.

171 W. E. Barnette, *J. Am. Chem. Soc.*, *106* (1984) 452.

172 R. Filler, *Isr. J. Chem.*, *17* (1978) 71.

173 M. Zupan and A. Pollak, *J. Org. Chem.*, *42* (1977) 1559.

174 B. Zajc and M. Zupan, *J. Org. Chem.*, *47* (1982) 573.

175 S. P. Anand, L. A. Quaterman, P. A. Christian, H. H. Hyman and R. Filler, *J. Org. Chem.*, *40* (1975) 3796.

176 S. P. Anand, L. A. Quaterman, H. H. Hyman, K. G. Migliorese and R. Filler, *J. Org. Chem.*, *40* (1975) 807.

177 D. H. R. Barton, J. Lister-James, R. H. Hesse, M. M. Pechet and S. Rozen, *J. Chem. Soc., Perkin Trans. 1*, (1982) 1105.

178 D. Alker, D. H. R. Barton, R. H. Hesse, J. Lister-James, R. E. Markwell, M. M. Pechet, S. Rozen, T. Takeshita and H. T. Toh, *Nouv. J. Chim.*, *4* (1980) 239.

179 T. Tsushima, K. Kawada and T. Tsuji, *J. Org. Chem.*, *47* (1982) 1107; T. Tsushima, K. Kawada, J. Nishikawa, T. Sato, K. Tori and T. Tsuji, *ibid.*, *49* (1984) 1163.

180 C. Gal and S. Rozen, *Tetrahedron Lett.*, *25* (1984) 449. See also S. Rozen and C. Gal, *J. Fluorine Chem.*, *27* (1985) 143.

181 M. Diksic and D. Jolly, *Carbohydr. Chem.*, *4* (1985) 265. See also M. Diksic and P. Di Raddo, *Tetrahedron Lett.*, *25* (1984) 4885.

182 See V. Grakauskas, *Intra-Sci. Chem. Rep.*, *5* (1971) 86.

183 C. M. Sharts, *J. Org. Chem.*, *33* (1968) 1008.

184 See, for example, K. O. Christe, *J. Fluorine Chem.*, *25* (1984) 269; M. M. Cartwright and A. A. Woolf, *ibid.*, *25* (1984) 263, and footnote 12 in ref. 162.

185 J. B. Levy and D. M. Sterling, *J. Org. Chem.*, *50* (1985) 5615.

186 See, for example, T. A. O'Donnell, 'The Chemistry of Fluorine', in *Comprehensive Inorganic Chemistry*, Chap. 25, Pergamon, Oxford, 1973; H. W. Schmidt and J. T. Harper, *Handling and Use of Fluorine and Fluorine–Oxygen Mixtures in Rocket Systems*, NASA (SP-3037), Washington, DC, 1967; J. Grannec and L. Lozano, in P. Hagenmuller (ed.), *Inorganic Solid Fluorides*, Academic, Orlando, FL, 1985, p. 17; M. Hudlicky, *Chemistry of Organic Fluorine Compounds*, Ellis Horwood, Chichester, 1976.

187 A. J. Woytek, *Kirk-Othmer's Encyclopedia of Chemical Technology*, Vol. 10, 1980, p. 643.

188 A. J. Rudge, *The Manufacture and Use of Fluorine and Its Compounds*, Oxford University Press, London, 1962.

189 W. R. Meyers, *Chem. Eng. Prog.*, *44* (1948) 359.

190 R. Lagow and J. L. Margrave, *Prog. Inorg. Chem.*, *26* (1979) 162.

191 W. T. Miller and A. L. Dittman, *J. Am. Chem. Soc.*, *78* (1956) 2793. See also W. T. Miller, S. D. Koch and F. W. McLafferty, *ibid.*, *78* (1956) 4992; W. T. Miller and S. D. Koch, *ibid.*, *79* (1957) 3084; W. T. Miller, J. O. Stoffer, G. Fuller and A. C. Currie, *ibid.*, *86* (1964) 51.
192 J. L. Margrave and R. J. Lagow, *Chem. Eng. News*, *63* (Jan. 12, 1970) 40.
193 D. F. Persico, H.-N. Huang, R. J. Lagow and L. C. Clark, *J. Org. Chem.*, *50* (1985) 5156.
194 R. E. Aikman and R. J. Lagow, *J. Org. Chem.*, *47* (1982) 2789.
195 See, for example, A. J. Atsuka and R. J. Lagow, *J. Fluorine Chem.*, *4* (1974) 371.
196 J. L. Adcock, K. Horita and E. B. Renk, *J. Am. Chem. Soc.*, *103* (1981) 6937.
197 J. L. Adcock and M. L. Robin, *J. Org. Chem.*, *49* (1984) 191.
198 M. A. Robinson, H. R. Nychka, J. B. Hino, R. E. Eibeck and J. I. Brauman, *Eur. Pat. 0 032 210* (1984) (to Allied Corp.); H. R. Nychka, J. B. Hino, R. E. Eibeck and M. A. Robinson, *Eur. Pat. Appl. 0 031 519* (1980) (to Allied Chemical Corp.).
199 J. M. Tedder, *Adv. Fluorine Chem.*, *2* (1961) 104.
200 E. A. Tyczkowski and L. A. Bigelow, *J. Am. Chem. Soc.*, *77* (1955) 3007.
201 A. F. Maxwell, F. E. Detoro and L. A. Bigelow, *J. Am. Chem. Soc.*, *82* (1960) 5827.
202 R. A. Powell (ed.), *Dry Etching for Microelectronics*, North-Holland, Amsterdam, 1984.
203 J. L. Margrave, R. H. Hauge, R. B. Badachape and R. J. Lagow, *Kirk-Othmer's Encyclopedia of Chemical Technology*, Vol. 10, 1980, p. 851.
204 B. G. Willoughby ('Non-TFE-based Fluoroplastics'), S. Smith ('Fluoroelastomers'), in R. E. Banks (ed.), *Preparation, Properties and Industrial Applications of Organofluorine Compounds*, Ellis Horwood, Chichester, 1982, pp. 204 and 263, respectively.
205 A. J. Woytek and J. F. Gentilcore, *Plast. Rubber Process.*, *4* (1979) 10.
206 See Chapter 4, ref. 128.
207 A. J. Rudge, *Br. Pat. 710 523* (1954) (to I.C.I.).
208 S. P. Joffre, *U.S. Pat. 2 811 468* (1957) (to Shulton Inc.).
209 N. Watanabe and T. Nakajima, in R. E. Banks (ed.), *Preparation, Properties, and Industrial Applications of Organofluorine Compounds*, Ellis Horwood, Chichester, 1982, p. 297.
210 D. T. Meshri, personal communication.
211 J. L. Margrave, R. G. Bautista, P. J. Ficalora and R. B. Badachape, *U.S. Pat. 3 711 595* (1973).
212 W. K. R. Musgrave, *Adv. Fluorine Chem.*, *1* (1960) 1.
213 K. R. Brower, *J. Fluorine Chem.*, *31* (1986) 333.
214 M. Stacey and J. C. Tatlow, *Adv. Fluorine Chem.*, *1* (1960) 166.
215 R. J. Kingdom, G. D. Bond and W. L. Linton, *Br. Pat. 1 281 822* (1972) (to I.S.C. Chemicals Ltd.).
216 P. L. Coe, A. W. Mott and J. C. Tatlow, *J. Fluorine Chem.*, *20* (1982) 167, and earlier papers cited therein.
217 J. Burdon, T. M. Hodgins, D. R. A. Perry, R. Stephens and J. C. Tatlow, *J. Chem. Soc.*, (1965) 808; A. Bergomi, J. Burdon and J. C. Tatlow, *Tetrahedron*, *22* (1966) 2551.
218 R. E. Banks, R. N. Haszeldine and J. B. Walton, *J. Chem. Soc.*, (1963) 5581; R. E. Banks, M. Bridge and R. N. Haszeldine, *J. Chem. Soc. (C)*, (1970) 48.
219 R. E. Banks, A. C. Harrison and R. N. Haszeldine, *J. Chem. Soc. (C)*, (1966) 2102; R. E. Banks, L. E. Birks and R. N. Haszeldine, *ibid.*, (1970) 201.
220 J. A. Oliver, R. Stephens and J. C. Tatlow, *J. Fluorine Chem.*, *22* (1983) 21; A. E. M. M. Khalil, R. Stephens and J. C. Tatlow, *ibid.*, *22* (1983) 31, 133.
221 D. J. Dodsworth, C. M. Jenkins, R. Stephens and J. C. Tatlow, *J. Fluorine Chem.*, *24* (1984) 41; M. E. Allen, R. Stephens and J. C. Tatlow, *ibid.*, *25* (1984) 309.
222 J. Burdon, G. E. Chivers and J. C. Tatlow, *J. Chem. Soc. (C)*, (1970) 2146.
223 P. L. Coe, R. G. Plevey and J. C. Tatlow, *J. Chem. Soc. (C)*, (1969) 1060.

224 A. J. Edwards, R. G. Plevey, I. J. Sallomi and J. C. Tatlow, *J. Chem. Soc., Chem. Commun.*, (1972) 1028.
225 J. Burdon, J. G. Campbell, I. W. Parsons and J. C. Tatlow, *J. Chem. Soc. (C)*, (1971) 352.
226 G. S. Phull, R. G. Plevey and J. C. Tatlow, *J. Chem. Soc., Perkin Trans. 1* (1984) 455; *idem, J. Fluorine Chem., 25* (1984) 111.
227 M. Brandwood, P. L. Coe, C. S. Ely and J. C. Tatlow, *J. Fluorine Chem., 5* (1975) 521.
228 R. D. Chambers, B. Grieveson, F. G. Drakesmith and R. L. Powell, *J. Fluorine Chem., 29* (1985) 323.
229 J. Burdon, I. W. Parsons and J. C. Tatlow, *Tetrahedron, 28* (1972) 43; J. Burdon and I. W. Parsons, *ibid., 36* (1980) 1423.
230 J. H. Simons Memorial Issue, *J. Fluorine Chem.*, (1986).
231 J. H. Simons, *J. Electrochem. Soc., 95* (1949) 47; J. H. Simons, H. T. Francis and J. A. Hogg, *ibid., 95* (1949) 53; J. H. Simons and W. J. Harland, *ibid., 95* (1949) 55; J. H. Simons, W. H. Pearlson, T. J. Brice, W. A. Wilson and R. D. Dresdner, *ibid., 95* (1949) 59; J. H. Simons and R. D. Dresdner, *ibid., 95* (1949) 64.
232 J. H. Simons (ed.), in *Fluorine Chemistry*, Vol. 1, Academic, New York, 1950, p. 414; J. H. Simons and T. J. Brice, *ibid.*, Vol. 2, 1954, p. 333.
233 J. Burdon and J. C. Tatlow, *Adv. Fluorine Chem., 1* (1960) 129; S. Nagase, *Fluorine Chem. Rev., 1* (1967) 77.
234 H. M. Fox, F. N. Ruehlen and W. V. Childs, *J. Electrochem. Soc., 118* (1971) 1246; W. V. Childs, *U.S. Pat. 3 558 449* (1971) (to Phillips Petroleum Co.).
235 F. G. Drakesmith and D. A. Hughes, ref. 230, p. 103.
236 F. W. Klink, F. Kucera, D. J. Wasser and C. C. Liu, ref. 230, p. 77; F. W. Klink, D. J. Wasser and C. C. Liu, ref. 230, p. 89.
237 G. G. I. Moore, J. C. Hansen, T. M. Barrett, J. E. Waddell, K. M. Jewell, T. A. Kestner and R. M. Payfer, ref. 230, p. 41.
238 G. P. Gambaretto, M. Napoli, L. Conte, A. Scipione and R. Armelli, *J. Fluorine Chem., 27* (1985) 149.
239 W. H. Pealson, ref. 230, p. 29.
240 F. Lombardo, *J. Fluorine Chem., 18* (1981) 1.
241 See, for example, B. D. Joyner and C. R. Patrick, in R. E. Banks (ed.), *Organofluorine Chemicals and Their Industrial Applications*, Ellis Horwood, Chichester, 1979, pp. 75 and 94, respectively; C. R. Patrick, in R. E. Banks (ed.), *Preparation, Properties and Industrial Applications of Organofluorine Compounds*, Ellis Horwood, Chichester, 1982, p. 193.
242 Fluorocarbons (*sic*), *Chem. Mark. Rep.*, (10 March, 1986).
243 J. L. Fox, *Chem. Ind. (London)*, (1985) 177.
244 *Eur. Plast. News, 13* (1986) 9.
245 D. K. Thomas, *Plast. Rubber Int., 8* (1983) 53; *idem, Shell Polym., 8* (1984) 37.
246 K. I. W. Bouch, *Shell Polym., 8* (1984) 42.
247 R. C. Bill and L. P. Ludwig, *Wear, 59* (1980) 165.
248 D. A. Kourtides, J. A. Parker and W. J. Gilwee, *J. Fire Flammability, 6* (1975) 373.
249 *Plast. Rubber Wkly.*, (May 4, 1985) 4.
250 A. E. Comyns, *Chem. Br., 22* (1986) 47.
251 W. J. Huong, *J. Fluorine Chem., 32* (1986) 179.

Appendix 11.1

Fluorocarbon nomenclature

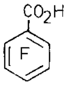
Fluorinated organic compounds, in general, are treated as hydrocarbon derivatives for the purposes of nomenclature (IUPAC and CAS). In the case of fluorocarbons and their derivatives, however, the use of Greek or Latin numeral roots to indicate the number of fluorines present [*e.g.* octafluoropropane (C_3F_8); dodecafluorocyclohexane (c-C_6F_{12}); pentadecafluoro-octanoic acid (n-$C_7F_{15}CO_2H$)] often results in cumbersome names and, more importantly, does not immediately reveal that the compounds are fluorocarbon in nature. Therefore, the use of the prefix *perfluoro* in conjunction with standard hydrocarbon nomenclature is often preferred (*e.g.* perfluoropropane; perfluorocyclohexane; perfluoro-octanoic acid). Full details regarding use of 'perfluoro nomenclature', introduced in 1952, can be found in ref. 120 listed at the end of the main text above. Sadly the rules are not always followed to the letter, particularly the all-important one that the term perfluoro denotes substitution of *all* hydrogen atoms attached to carbon atoms *only*, except when that would change the identity of a functional group [*e.g.* perfluorobutyraldehyde is C_3F_7CHO not C_3F_7COF (an acyl fluoride); perfluoropropionic acid is $C_2F_5CO_2H$ not $C_2F_5C(O)OF$ (an acyl hypofluorite); perfluorodimethylamine is $(CF_3)_2NH$ not $(CH_3)_2NF$ (perfluoro-*N*-fluorodimethylamine)]. Hydrogen attached to carbon in an otherwise perfluorinated group is indicated by a prefix consisting of a numerical locant and the symbol *H*; for example, $CF_3CHFCHF_2$ is 1*H*,2*H*-hexafluoropropane and $CHF_2CF_2CF_2CF_2CO_2H$ is 5*H*-octafluoropentanoic acid.

Twelve years ago an alternative system was authorised by the American Chemical Society (see J. A. Young, *J. Chem. Doc.*, *14* (1974) 98) whereby the symbol *F* conveys the sense of perfluoro. This system has not been widely used yet, hence in this book we have followed the fairly common practice of standardising on neither IUPAC nor perfluoro nomenclature, but used them interchangeably. According to '*F*-nomenclature', C_3F_7CHO is *F*-butyraldehyde, $C_2F_5CO_2H$ is *F*-propionic acid and $(CF_3)_2NH$ is di(*F*-methyl)amine. The prefix *hydryl* is used to denote replacement of fluorine by hydrogen in a fluorocarbon system; for example CF_3CHFCF_3 is 2-hydryl-*F*-propane.

Interestingly, Simons disliked perfluoro terminology and unsuccessfully advocated [1] the adoption of a separate and distinct nomenclature for the field of fluorocarbon chemistry based on placement of the syllable *for* before the final syllable in an otherwise standard name, *e.g.* methforane (CF_4), ethforene (C_2F_4). Grosse and Cady [2] proposed the forerunner of the *F*-system described above but used the Greek letter phi (*e.g.* ϕ-heptane, C_7F_{16}) instead of the Latin F.

The use of a small subscript F (or f) in conjunction with the conventional symbols R and Ar to represent general cases of monovalent perfluoroalkyl (R_F) or perfluoroaryl (Ar_F) groups is very well established. Also common is the placement of a large F in the centre of ring structures to symbolise that all substituents not shown are fluorine, *e.g.*

perfluorocyclobutane



pentafluorobenzoic acid

Finally, the practice has arisen lately of referring to fluorocarbons as perfluorocarbons to make clear that they are composed of *only* carbon and fluorine. This has come about through mis-use of the former term — a situation we find regrettable but inevitable.

References

1 J. H. Simons, *Fluorine Chem.*, *I* (1950) 404.

2 A. V. Grosse and G. H. Cady, *Ind. Eng. Chem.*, *39* (1947) 367.

Appendix 11.2

Nuclear magnetic resonance

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With 100% natural abundance, high magnetogyric ratio and spin number (I) of $\frac{1}{2}$, ^{19}F is only some 20% less sensitive than ^{1}H, and resonates at a radiofrequency 94% of that of ^{1}H. It is therefore not surprising that applications in inorganic, organic and organometallic chemistry have been widespread since the early days of NMR spectroscopy.

The fluorines in different chemical environments in, for example, a polyfluoroaromatic compound were reported by Gutowsky and Hoffmann [1] to show different chemically shifted signals as early as 1950, *i.e. before* the well-known report of different ^{1}H chemical shifts in ethanol and other alcohols by Arnold, Dharmatti and Packard [2]. ^{19}F NMR spectroscopy has a substantial advantage over ^{1}H NMR spectroscopy in that the range of chemical shifts is much larger — over 400 ppm for organofluorine compounds and some 700 ppm if inorganic compounds are included (Fig. 2.1). The ranges of ^{19}F chemical shifts for individual structural types can also be large (see Fig. 2.1), but can be further subdivided according to substituents, just as, for example, the ^{1}H shift for CH_3X depends on the nature of the substituent X. By 1951, ^{19}F chemical shifts for substituted fluorobenzenes had been related to Hammett substituent constants, and the correlation of shifts with these and other substituent constants has been of continuing interest ever since [3]. Also in 1951, field-independent splitting

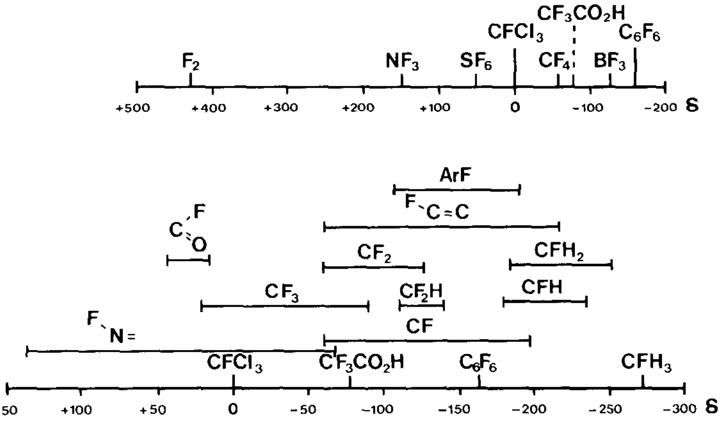


Fig. 2.1. ^{19}F chemical shifts in parts per million.

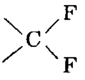
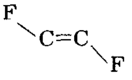
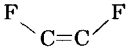
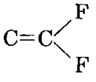
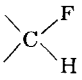
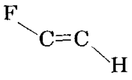
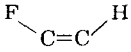
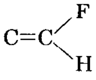
of signals by indirect spin–spin coupling involving ^{19}F was noted in $NaSbF_6$ (albeit in the ^{121}Sb and ^{123}Sb spectra) by Proctor and Yu [4], and in the ^{19}F and ^{31}P spectra of compounds such as $POFCl_2$ and POF_2Cl by Gutowsky and McCall [5]. Spin–spin coupling, both between magnetically distinct fluorine sets and from fluorine to hydrogen is commonly stronger than between magnetically different hydrogen sets (Table 2.1) and the coupling can be observed not only through more bonds but also through space, given favourable geometries. This often leads to highly complicated spectra which nevertheless yield to first-order analysis. Although the coupling constants are large, they are still, in many cases, only a small fraction of the chemical shifts involved, and the analysis to obtain the coupling constants then rests mainly on measurement of the line spacings and intensities, intuition and persistence (Fig. 2.2). Spin–spin decoupling has been much less used than in ^1H NMR spectroscopy to simplify complicated spectra, largely because of instrumental limitations. Higher order spectra can, of course, be analysed by use of iterative computer programmes (*e.g.* LAOCOON 3, LAME) in the same way as ^1H spectra.

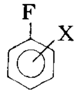
Experimental methods

Instruments capable of ^{19}F spectroscopic observations have been commercially available since the late 1950s but even where only a dedicated

TABLE 2.1

Some fluorine–fluorine and fluorine–hydrogen coupling constant ranges

			
40 - 370 Hz	100 - 150 Hz	0 - 60 Hz	0 - 110 Hz
			
40 - 80 Hz	10 - 50 Hz	0 - 20 Hz	70 - 90 Hz
CFX_2CFY_2	$CFX_2CZ_2CFY_2$	$CFX_2CZ_2CQ_2CFY_2$	
0 - 40 Hz	6 - 14 Hz	0 - 18 Hz	

	X	J_{FX}/Hz	X	J_{FX}/Hz	X	J_{FX}/Hz
	ortho-F	18 - 35	*meta*-F	0 - 15	*para*-F	4 - 16
	ortho-H	7 - 12	*meta*-H	4 - 8	*para*-H	0 - 3

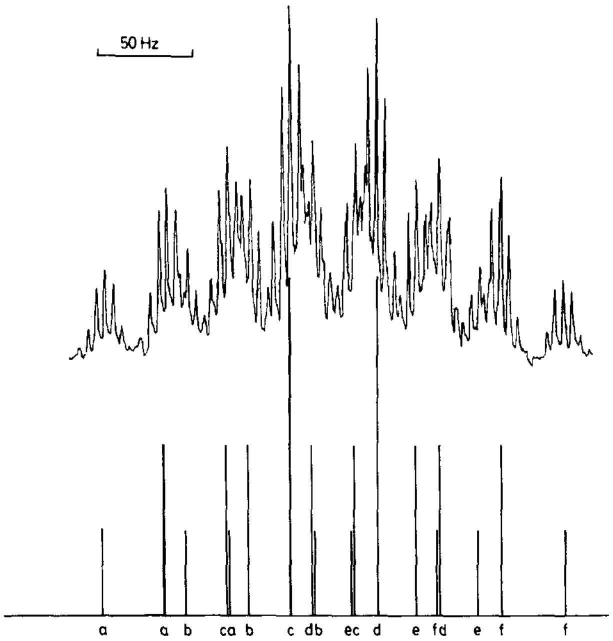


Fig. 2.2. The ^{19}F resonance spectrum of the single fluorine in $(CF_3)_2PCH_2CH_2F$ at 56.46 MHz. The resonance is a 46.9 Hz triplet of 31.4 Hz doublets of 23.2 Hz triplets of 3.9 Hz septets. The splitting diagram shows the six triplets (a - f), each band of which is further split in the spectrum into 3.9 Hz septets.

^1H instrument is available, useful information about the fluorine environments can be obtained from any ^1H–^{19}F couplings visible in the ^1H spectrum. Experimentally, 5 mm diameter sample tubes are commonly used, as for ^1H NMR spectroscopy, but the high volatility of many fluorine compounds often makes it desirable to have the sample sealed in glass. In such cases, a sealed 4 mm tube which fits loosely inside a standard 5 mm NMR sample tube, or even a sealed melting point capillary tube can be used to avoid sealing the more expensive sample tube. With locking solvent or external reference in the annulus there is usually no need to support the capillary centrally unless the highest resolution is needed. Acceptable spectra can be obtained in this way with neat liquids or reasonably concentrated solutions even with a 2.1 Tesla CW instrument. For more dilute solutions the use of a Fourier Transform spectrometer is desirable. A useful reference compound for ^{19}F NMR spectroscopy, introduced by Filipovitch and Tiers [6], is trichlorofluoromethane as an internal standard, but where the volatility of this compound is inconvenient, hexafluorobenzene (as either internal or external reference) or trifluoroacetic acid (as external reference) are often used.

Shifts to high field of internal trichlorofluoromethane were originally accompanied by the symbol ϕ^* (phi starred; positive values) or, if extrapolated to infinite dilution, by the symbol ϕ [6]; this has now given way to the δ scale, on which shifts to *low* field (*i.e.* to high frequency) of the reference are assigned *positive* values. Unfortunately, some authors omit to specify either the reference compound used or the sign convention, or both, leaving the chemical shifts quoted in their publications subject to considerable uncertainty which cannot always be resolved by consulting lists of firmly established data.

Structural identification of the components of mixtures by ^{19}F NMR spectroscopy is often easier than the corresponding problem in ^{1}H NMR spectroscopy, simply because the wider range of chemical shifts allows more ready separation of the signals. Integration of the separate ^{19}F signals then allows quantitative analysis of the composition, just as in a favourable ^{1}H analysis.

Carbon-13 NMR spectroscopy

Since the early 1970s, ^{13}C NMR spectrometers have become widely available. ^{13}C resonances are usually observed with simultaneous broadband ^{1}H decoupling, which both collapses the spin–spin multiplets that would otherwise arise from coupling of the individual ^{13}C nuclei to the several sets of hydrogens up to three or more bonds away, and also increases the intensity of the ^{13}C signals by the nuclear Overhauser effect (nOe). Under these conditions, the signals of carbons carrying fluorine but no hydrogen not only lack Overhauser enhancement, but are also split by spin–spin coupling to the fluorine, and may require prolonged accumulation for observation.

For fluorocarbon compounds, use of broad-band ^{19}F decoupling instead of ^{1}H decoupling appears an obvious solution, and is possible, but often time-consuming. The large chemical shift range for ^{19}F and the large ^{13}C–^{19}F couplings are in this respect an embarrassment, since the power required for broad-band decoupling, even at a modest 1.9 Tesla (80 MHz for ^{1}H, 75.3 MHz for ^{19}F, 20.1 MHz for ^{13}C) is of the order of tens of watts, compared with 1 - 3 W for hydrogen decoupling. A waiting period of five to ten times the duration of the high-power decoupling is thus necessary between pulses to prevent an unacceptable temperature rise, not only of the sample but of the probe itself. Triple resonance experiments, in which both ^{1}H and ^{19}F are simultaneously decoupled whilst ^{13}C is observed, have been reported [7], but the facilities are not routinely available, and the usual way of obtaining ^{13}C information on a compound containing both hydrocarbon and fluorocarbon (or hydrofluorocarbon) groups is to run two spectra, one with ^{1}H and the other with ^{19}F decoupling.

The higher sensitivity and dispersion available for ^{13}C with modern spectrometers using superconducting magnets and high-sensitivity probes makes the use of broad-band ^{19}F decoupling less necessary than with low-field systems, but caution is needed in analysis of the fully coupled spectra, since line spacings may not correspond simply to coupling constants by reason of close-coupling of the fluorines in the isotopic species under observation.

Few reports have so far appeared of the application of modern pulse sequences for spectrum enhancement and editing, or of 2-D spectroscopy to organofluorine compounds [8]. Practical problems of decoupler power and heating effects will clearly be important where several chemically shifted fluorines are present in a sample, and may limit the use of these techniques, *e.g.* to the enhancement of the ^{13}C signal of a single CF_3 group in a large molecule.

Some major reviews of NMR spectroscopy in fluorine chemistry, and useful compilations of data, are listed below [9 - 15].

References

1 H. S. Gutowsky and C. J. Hoffman, *Phys. Rev., 80* (1950) 110.
2 J. T. Arnold, S. S. Dharmatti and M. E. Packard, *J. Chem. Phys., 19* (1951) 507.
3 See D. F. Ewing, in N. B. Chapman and J. Shorter (eds.), *Correlation Analysis in Chemistry: Recent Advances,* Plenum, New York, 1978.
4 W. G. Proctor and F. C. Yu, *Phys. Rev., 81* (1951) 20.
5 H. S. Gutowsky and D. W. McCall, *Phys. Rev., 82* (1951) 748.
6 G. Filipovitch and G. V. D. Tiers, *J. Phys. Chem., 63* (1959) 761.
7 M. A. Hamza, G. Serratrice and J.-J. Delpuech, *Org. Magn. Reson., 16* (1981) 98.
8 See, for example, J. T. Gerig, *Macromolecules, 16* (1983) 1797; S. J. Hammond, *J. Chem. Soc., Chem. Commun.,* (1984) 712; M. Pons, M. Feliz and E. Giralt, *Tetrahedron Lett., 26* (1985) 2817.
9 J. W. Emsley, J. Feeney and L. H. Sutcliffe, *High Resolution Nuclear Magnetic Resonance Spectroscopy,* Chap. 11, Pergamon, Oxford, 1966.
10 C. H. Dungan and J. R. Van Wazer, *Compilation of Reported ^{19}F NMR Chemical Shifts, 1951 to mid-1967,* Wiley-Interscience, New York, 1970.
11 J. W. Emsley and L. Phillips, *Prog. Nucl. Magn. Reson. Spectrosc., 7* (1971) 1.
12 J. W. Emsley, L. Phillips and V. Wray, *Fluorine Coupling Constants,* Pergamon, Oxford, 1977; *idem, Prog. Nucl. Magn. Reson. Spectros., 10* (1977) 85.
13 M. G. Barlow, in *Fluorocarbon and Related Chemistry* (Royal Society of Chemistry Specialist Periodical Report Series), Vol. 1, 1971, p. 270 and Vol. 2, 1974, p. 456.
14 See, E. F. Mooney and P. H. Winson, *Annu. Rep. NMR Spectrosc., 1* (1968) 244; K. Jones and E. F. Mooney, *ibid., 3* (1970) 261 and *4* (1971) 391; R. Fields, *ibid., 5A* (1972) 99 and *7* (1977) 1; L. Cavalli, *ibid., 6B* (1976) 43; V. Wray, *ibid., 10B* (1980) 1 and *14* (1983) 1.
15 All volumes of *Nuclear Magnetic Resonance* (Royal Society of Chemistry Specialist Periodical Report Series), contain sections on ^{19}F chemical shifts and coupling constants.

BIOGRAPHIC NOTE

After graduation from Cambridge in 1957, Roy Fields moved to U.M.I.S.T. with Professor R.N. Haszeldine to work for a Ph.D. degree in preparative organofluorine chemistry. He was appointed to the academic staff in 1960 and became a Senior Lecturer in 1972. In addition to his wide-ranging studies in synthetic organic chemistry, he has been in charge of the NMR spectroscopic service at U.M.I.S.T. for more than 20 years.

R. Fields

Appendix 11.3

Elemental analysis of organofluorine compounds

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This short article is based on experience gained during the past 30 years by the analytical staff of the Chemistry Department at U.M.I.S.T. through dealing with vast numbers of new compounds of many types synthesised by members of the Manchester fluorine school. Readers seeking more information are advised to consult initially refs. 1 and 2 below. These give good background information on the various working procedures for fluorine analysis.

Determination of fluorine content

Quantitative analysis for covalently-bound fluorine comprises two operations: (a) destruction of all C—F, N—F, S—F, *etc.* bonds to produce fluoride ions; and (b) determination of the amount of fluoride produced. Because of the great strength of the C—F bond, organic compounds containing fluorine are sometimes difficult to decompose completely ('mineralise'); this is particularly true for fluorocarbon-type compounds, especially nitrogen derivatives. The main methods of decomposition are (i) alkali-metal fusion (Na or K), (ii) peroxide bomb (Ni or Parr bomb), (iii) tube combustion (pyrohydrolysis) or (iv) oxygen flask (Schöniger).

Owing to attack of sodium or potassium on silica at elevated temperatures, the alkali-metal fusion procedure is traditionally carried out in a nickel tube or bomb [3], and involves reaction of 30 - 40 mg of alkali metal with 3 - 5 mg of a fluorinated compound at 600 °C. However, recent work [4] has shown that complete decomposition can be achieved in glass ampoules at much lower temperatures (280 °C). Production of cyanide and sulphide should nitrogen or sulphur be present is always a nuisance, however. Although the oxidative fusion technique (employing sodium peroxide [5]) overcomes these problems, it too involves the final production of a solution of fairly high ionic strength, which may present difficulties in the subsequent fluoride determination. Most types of fluorinated material can be decomposed satisfactorily by the peroxide bomb method.

The tube-combustion technique involves heating the sample in moist air [6] or O_2, and passing the combustion products over platinised silica held in a silica tube at 1100 °C. Very effective decomposition of fluorocarbons (including gaseous or highly-volatile compounds) occurs, and the HF formed is swept into an absorbent — usually water. Only if the sample being analysed contains boron are problems encountered, and the peroxide-bomb method is the best for such samples [7].

The oxygen-flask combustion procedure [8] in which the sample, wrapped in filter paper, is burned in oxygen in a silica conical flask, is now very popular owing to its low cost and simplicity. It can give problems, however, with highly-fluorinated materials which release gaseous low-molecular-weight fluorocarbon species during combustion.

In our experience, the tube-combustion decomposition procedure is the best of these four methods because (a) it allows some variation of combustion conditions to cope with different sample types (chemically and physically) and (b) it yields a fluoride solution of low ionic strength. Once set up, it is easy to use and less hazardous than the peroxide-bomb method. The oxygen-flask procedure is satisfactory for most fluorine-containing materials providing they undergo complete combustion within the inherent short ignition period.

Determination of fluoride ion

There are four main methods for determining fluoride ions in solution: (i) acidimetric titration (of HF); (ii) colorimetric determination (titration, bleaching, direct colour); (iii) fluoride ion-selective electrode (potentiometry, La^{3+} titration); and (iv) ion chromatography.

Providing no other acidic species are present and water has been used as the absorption medium, the acid–base titration of HF is the simplest and easiest method for fluoride determination. This is particularly applicable to the oxygen-flask or tube-combustion methods of decomposition. Unfortunately other acidic species are often present. In the case of the sodium fusion and peroxide-bomb methods of decomposition, which provide highly alkaline solutions, colorimetric methods are often applicable based on the capacity of fluoride ion to bleach coloured complexes derived from Zr, Th, Ti or Fe. If the fluoride ion can be isolated from the sample, titrimetric procedures employing the salts of Al, Th, Zr or Ce can be followed [5]. The most popular colorimetric procedure, and the one we have used successfully for many years, is that employing the Ce–alizarin complexone [9], which changes from wine red to bluish-purple in the presence of fluoride ion. A sulphonated Ce–alizarin complex [10] is reported to be even more sensitive to fluoride ion, and more stable in solution than its parent complex, but it is less readily available.

The arrival of the fluoride ion-selective electrode greatly assisted fluoride ion determination, especially after sample destruction by either the oxygen-flask or tube-combustion method. Fluoride ion has been determined either by direct potentiometry [11] or potentiometric titration with Th^{4+} or La^{3+}, using the electrode as an end-point indicator. Much work has gone into perfecting the La^{3+} *versus* F^- titration involving Gran plot modifications to improve the rather sluggish end-point detection [8]. Ion chromatography is the very latest technique to be applied to fluoride ion determination [4], again following either a tube-combustion [12] or an oxygen-flask decomposition [12]. It is both very sensitive (to ppb levels of F^- in the sample solution) and rapid, and will quantify other anions as well — which makes it valuable for mixed halogen determinations.

The Ce–alizarin colorimetric method is likely to be the most precise and cheapest means of determining fluoride ion concentrations, but it is rather time-consuming except when used in conjunction with flow-injection techniques. The commercially-available fluoride ion-selective electrode is easy to use but can suffer from drift problems when used in direct potentiometry. Ion chromatography is excellent if the equipment is available, and is best suited to low levels of fluoride determination.

Carbon, hydrogen and nitrogen analysis

All the modern automatic CHN elemental analysers will cope satisfactorily with the vast majority of fluorine-containing compounds. Very highly fluorinated materials sometimes need combustion aids and extended combustion times to ensure complete decomposition.

References

1 L. Mazor, *Analytical Chemistry of Organic Halogen Compounds*, Pergamon, New York, 1975, Ch. 4.

2 M. Hudlicky, *Chemistry of Organic Fluorine Compounds*, Chap. 8, Ellis Horwood, Chichester, 1976.

3 R. Belcher, E. F. Caldas, S. J. Clark and A. Macdonald, *Mikrochim. Acta*, *3/4* (1953) 283.

4 C. Y. Wang and J. G. Tarter, *Anal. Chem.*, *55* (1983) 1775.

5 C. Eger and A. Yarden, *Anal. Chem.*, *28* (1956) 512.

6 G. J. Kakabadse, B. Manohin, J. Bather, E. C. Weller and P. Woodbridge, *Nature (London)*, *229* (1971) 626.

7 R. C. Rittner and T. S. Ma, *Mikrochim. Acta*, (1972) 405.

8 G. J. Davies and M. A. Leonard, *Analyst*, *110* (1985) 1205.

9 R. Belcher, M. A. Leonard and T. S. West, *J. Chem. Soc.*, (1959) 3577.

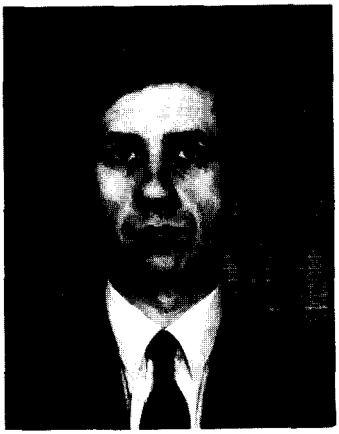
10 M. A. Leonard, S. F. Deane, V. McKee and G. Svehla, *Analyst*, *103* (1978) 1134.

11 M. Terry and F. Kasler, *Mikrochim. Acta*, (1971) 569.

12 R. Perry, unpublished results.

BIOGRAPHIC NOTE

Roger Perry is a Senior Experimental Officer in the Microanalytical Department at UMIST. He graduated (B.Sc.) from Nottingham University in 1963, and then gained experience as a research analyst in the phosphorus industry [Albright and Wilson (mfg) Ltd.]. The years 1967 - 70 were spent in Manchester University's Radiological Protection Service, where his work on the movement of radionuclides in food chains led to the award of the Ph.D. degree in 1971, the year in which he took up his present post.



R. Perry

Appendix 11.4

The work of I. L. Knunyants and the school of organofluorine chemistry at the Institute of Organoelemental Compounds, Moscow (U.S.S.R.)

The distinguished Russian fluorine chemist Ivan Lyudvigovich Knunyants was born in 1906, and after World War II he created the very large school of organofluorine chemistry at the Institute of Organoelemental Compounds of the U.S.S.R. Academy of Sciences. With a host of collaborators, he has published over 1000 papers, very many of them on organofluorine chemistry, though he has also worked in general organic chemistry on drug synthesis (this includes 5-fluorouracil) and on caprolactam. He is still publishing in fluorocarbon chemistry. The range of his major interests (and the names of some of his senior colleagues) are indicated in refs. 14, 60 and 107 in the main text, and in the following selection of his other review articles.

I. L. Knunyants

1 'Reactions of the carbonyl group in fluorinated ketones', with N. P. Gambaryan, E. M. Rokhlin, Yu. V. Zeifman and Ching-Yun Chen, *Angew. Chem., Int. Ed. Eng., 5* (1966) 947.
2 'Some aspects of the reactivity of fluoro-olefins', with B. L. Dyatkin, *Zh. Vses. Khim. Ova., 15* (1970) 5.
3 'Mesomeric carbanions of fluorine-containing monocarbonyl compounds', with E. M. Rokhlin and Yu. A. Cheburkov, *Zh. Vses. Khim. Ova., 15* (1970) 15.
4 'Perfluorovinyl derivatives of certain elements', with R. N. Sterlin and B. L. Isaev, *Zh. Vses. Khim. Ova., 15* (1970) 25.
5 'Fluorinated β-sultones', with G. A. Sokolskii, *Angew. Chem., Int. Ed. Eng., 11* (1972) 583.

6 'Advances in synthesis and study of organofluorine compounds', with V. R. Polishchuk, *Usp. Khim.*, *44* (1975) 685.

7 'New Data on reactions of organofluorine compounds', with V. R. Polishchuk, *Usp. Khim.*, *45* (1976) 1139.

8 'Present state and prospects of the development of the most important fluorine-containing materials', with I. L. Serushkin, Yu. A. Panshin and S. V. Sokolov, *Zh. Vses. Khim. Ova.*, *25* (1980) 552.

9 'Fluorine-containing halomethylene phosphoranes', with V. V. Tyuleneva and E. M. Rokhlin, *Usp. Khim.*, *50* (1981) 522.

10 'Fluorine-containing phosphorus ylids', with V. V. Tyuleneva and E. M. Rokhlin, *Usp. Khim.*, *51* (1982) 3.

11 'The synthesis and properties of aliphatic fluoronitroso-compounds', with Yu. A. Sizov and O. V. Ukharov, *Usp. Khim.*, *52* (1983) 976.

12 'The chemistry of perfluoroisobutene', with Yu. V. Zeifman, E. G. Ter-Gabrielyan and N. P. Gambaryan, *Usp. Khim.*, *53* (1984) 431.

English translations of the journal *Uspekhi Khimii* are available as *Russian Chemical Reviews.*

Appendix 11.5

Discovery of a fluorine-stable perfluoroalkyl radical

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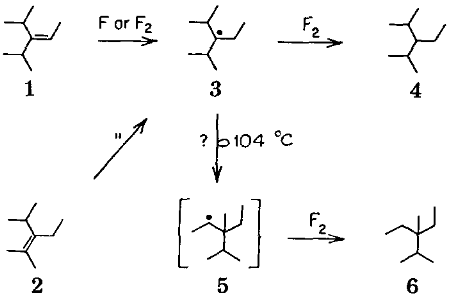
Since its first appearance in Moissan's laboratory, fluorine has held a well-deserved reputation as the most reactive of the elements, so it was not expected that a relatively simple alkyl *free radical* could be prepared *in bulk* by the reaction of undiluted fluorine with a perfluoroalkene. My co-workers and I were privileged to make this surprising discovery [1] and I will describe here how the discovery came about and speculate somewhat on the lesson it provides about elemental fluorine chemistry.

Koh Yamanouchi and I had just set up a fluorine line in early 1980 and were preparing to test a scheme for direct fluorination in solution, an essential feature of which was the use of undiluted fluorine [2]. Neither of us had worked with F_2 in *any* concentration before, so we decided to gain experience with this feared substance by repeating some published work on the fluorination of the hexafluoropropene trimers **1** and **2** by von Halasz, Kluge and Martini [3]. This paper had already caught our attention because of the authors' proposal of an unusual rearrangement when the reaction was carried out above 100 °C: an intramolecular 1,2-alkyl shift in a postulated intermediate free radical, **3** → **5**, giving finally the isolated product **6** (Scheme 5.1). We knew that such rearrangements in free radicals are rare and thought to occur only by dissociation–recombination processes [4], which seemed impossible in the presence of elemental fluorine. So we considered that the German workers might have misassigned structure **6**.



Scheme 5.1.^{a}

^{a}Skeletal or stick formulae are used here for clarity, with the fluorine substituents omitted. All the molecules are perfluorinated; thus, for example, trimer 1 is $[(CF_3)_2CF]_2C{=}CFCF_3$.

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But when we repeated their work we completely confirmed the reported results and, despite bringing to bear some more modern spectroscopic techniques, could find no basis for changing the original structural assignments.

Because we used a simple apparatus, absorption of fluorine at room temperature was slower than expected; and unsure that the GC columns we had on hand would separate the components of the reaction mixture, we chose to follow reaction progress using ^{19}F NMR spectroscopy. To our surprise, the sharp peaks of the starting trimers disappeared after the introduction of much less than 1 equiv of fluorine; deciding that we must have miscalculated the amount of fluorine passed, we proceeded to work up the mixture, using as one step a wash with diethylamine. When the amine wash was performed, much heat was evolved, and upon re-taking the ^{19}F NMR spectrum of the mixture, we found it to consist almost entirely of starting material! Only on repeating the fluorination for a much longer reaction time did we succeed in preparing the saturated perfluoroalkane 4. (We now know that radical 3 is a strong oxidant and is destroyed by mild reducing agents, via single-electron transfer followed by loss of fluoride ion.)

Koh and I moved on to other work from these puzzling observations, but did consider the possibility that some paramagnetic species, *i.e.* a free radical, was responsible for the NMR line broadening. We were aware that Krusic, Chen, Meakin and Kochi [5] as well as Malatesta, Forrest and Ingold [6] had observed some long-lived fluorinated alkyl radicals which seemed to be much more persistant than their nearest nonfluorinated relatives [7], but we were still not prepared to believe that we might have made radicals in more than spectroscopic concentrations. Only some months later, after a visit to U.S.C. by Harold Goldwhite, did we decide to have a look at the mixture by ESR spectroscopy in the former's laboratory. When we did, what we found was astonishing: not only were radicals present in our mixture in unusually high concentrations, judging from the multiple dilutions required before exchange-broadening began to diminish, but we found that the samples could be diluted in the open air and dissolved in good hydrogen donors like toluene, or heated to 100 °C, without destroying the ESR signals. A partial analysis of the ESR spectrum showed it to be consistent with a radical of structure 3.

Soon after these observations, Taizo Ono arrived in my laboratory and began seriously to study this unusual radical. Using Evans' method [8], he followed the increase in paramagnetism with fluorination time and showed that the concentration of the radicals reached about 35% by weight, starting with a 1:2 mixture of trimers 1 and 2. Having no prejudice to the contrary, he even showed that the radical build-up could be followed by GC if the injector and detector temperatures were set to 100 °C or lower, and his GC analyses agreed well with the magnetic measurements. GC analyses also allowed him to show that 1 is consumed faster than 2 but both give 3; since 3 reacts very slowly with fluorine to give 4, it followed that the yield of 3 would be higher if we could start with pure 1. Rick Fernandez then did a tedious distillation* to obtain some pure 1 and found that the maximum radical concentration during fluorination at room temperature reached 88%!

Since the reaction of fluorine with 1 to give 3 cannot occur by a chain process, we have a rare opportunity to study in isolation the *initiation* step in a fluorination. Preliminary data indicate that the reaction is first-order in alkene, unlike the termolecular initiation step in the iodine–styrene reaction studied by Fraenkel and Bartlett. If that is so, then presumably a fluorine atom is formed simultaneously with 3, and even the F atom must react with high selectivity with the less-hindered end of the double bond in another molecule of 1

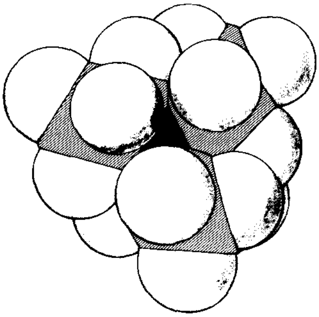

Fig. 5.1. Computer-generated space-filling picture of radical 3, based on standard bond lengths and van der Waals' radii; the unpaired electron is shown in black. This view is of the less-hindered face.

Steric hindrance (Figure 5.1†) is undoubtedly responsible for the remarkably sluggish reaction of 3 with fluorine and for its stability towards oxygen. We may ask just how much steric crowding is needed to stabilize a perfluoroalkyl radical with respect to dimerization: it now appears that the secondary perfluoro(2,4-dimethylpent-3-yl) radical is indefinitely stable to dimerization while its lower homologue perfluoro(2-methylpent-3-yl), though detectable for many hours in the absence of oxygen, does dimerize slowly. In surprising contrast, the tertiary perfluoro(2-methylpent-2-yl) radical appears much less persistent.

Further work supports our proposal [1] that the rearrangement product 6, correctly identified by von Halasz *et al.* [3], does in fact arise by an efficient *intermolecular* trifluoromethyl migration, the more remarkable because the CF_3 radical must make its way through a solution saturated with fluorine. We were first led to this hypothesis by lack of a better alternative, but have since found support in an earlier paper by Vedeneev, Teitel'boim and Shoikhet, who showed that trifluoromethyl radical reacts

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*The trimers 1 and 2 boil at 110 °C and 114 °C, respectively [9].

†Provided by A. J. Arduengo using the CHEMGRAF program.

selectively with triplet oxygen in the presence of an excess of fluorine, the extrapolated selectivity factor being 23 at 104 °C [10].

The most gratifying aspect of our discovery is that it reveals new subtleties in the chemistry of elemental fluorine, a substance still to be respected for its great reactivity but no longer to be feared as uncontrollable or dismissed as unselective.

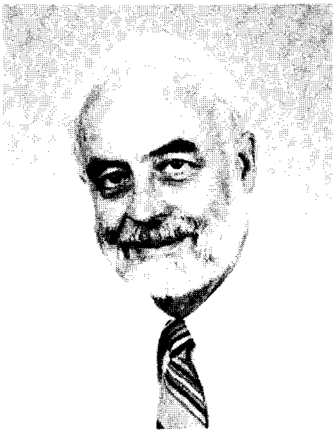
Acknowledgement

In addition to those named here, valuable contributors to this project include Paul Krusic (Central Research Department, E. I. Du Pont de Nemours & Co.) and Philip B. Henderson of U.S.C. Some of the work was done while the author was a Visiting Scientist at Du Pont. Financial support at U.S.C. was provided by the Green Cross Corporation of Osaka, Japan, and the 3M Company.

References

1 K. V. Scherer, Jr., T. Ono, K. Yamanouchi, R. Fernandez, P. Henderson and H. Goldwhite, *J. Am. Chem. Soc.*, *107* (1985) 718.
2 K. V. Scherer, Jr., T. Ono and K. Yamanouchi, 'Synthesis of Perfluorochemicals by Photofluorination in Solution Using 100% Fluorine', in R. B. Bolin, R. P. Geyer and G. J. Nemo (eds.), *Advances in Blood Substitute Research* (Vol. 122 of *Prog. Clin. Biol. Res.*), Alan R. Liss, Inc., New York, 1983, p. 450.
3 S. P. von Halasz, F. Kluge and T. Martini, *Chem. Ber.*, *106* (1973) 2950.
4 J. A. Berson, C. J. Olsen and J. S. Walia, *J. Am. Chem. Soc.*, *84* (1962) 3337.
5 P. J. Krusic, K. S. Chen, P. Meakin and J. K. Kochi, *J. Phys. Chem.*, *78* (1974) 2036.
6 V. Malatesta, D. Forrest and K. U. Ingold, *J. Phys. Chem.*, *82* (1978) 2370.
7 D. Griller and K. U. Ingold, *Acc. Chem. Res.*, *9* (1976) 13.
8 D. F. Evans, *J. Chem. Soc.*, (1959) 2003.
9 N. Ishikawa and M. Maruta, *Nippon Kagaku Kaishi*, (1977) 1411.
10 V. I. Vedeneev, M. A. Teitel'boim and A. A. Shoikhet, *Bull. Acad. Sci. USSR, Div. Chem. Sci.*, (1977) 480.

BIOGRAPHIC NOTE



K. Scherer

Kirby Scherer was born in Evansville, Indiana, and received his B.S., M.S. and Ph.D. degrees from Harvard University, the last in 1963 with the late R. B. Woodward. He joined the faculty of the University of California at Berkeley in 1962, and in 1967 moved to the University of Southern California. He spent the 1984 - 5 academic year in Wilmington, Delaware, as a Visiting Scientist with Du Pont and will move there on a permanent basis in 1986.

Appendix 11.6

Bibliography of organofluorine chemistry

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The first monograph on fluorine chemistry, Moissan's *Le Fluor et ses Composés*, published in 1900 [1], not only records the exploits of the 'Father of Fluorine Chemistry' but also contains a complete list of the literature on fluorine and its compounds available at the time (some 565 references, ordered both alphabetically and chronologically are quoted). It was 20 years before a second book, Otto Ruff's manual [2a] for the preparation of inorganic fluorides, appeared. The first specialist book on organic fluorine compounds was written by Bockemüller, and became available in 1936 [2b]. The commercialization of chlorofluoromethanes as refrigerants in the early 1930s, followed by the use of fluorinated compounds in connection with the atomic energy industry (Manhattan Project), triggered much interest in fluorine chemistry. This resulted in the publication of several reviews. The March 1947 issue of *Industrial Engineering Chemistry* [3], for example, was devoted totally to wartime developments; and an even fuller account of work carried out as part of the atomic bomb project appeared in a monograph edited by Slesser and Schram [4].

Systematic coverage of *all* aspects of fluorine chemistry did not start until three series of monographs began to be published: Simons' *Fluorine Chemistry* (five volumes [5]), Stacey, Tatlow and Sharpe's *Advances in Fluorine Chemistry* (seven volumes [6, 7]) and Tarrant's *Fluorine Chemistry Reviews* (eight volumes [8]). A fourth series, *Fluorocarbons and Related Chemistry*, designed to provide systematic coverage of accomplishments specifically in organic and organo-elemental fluorine chemistry over two-year periods, was initiated by Banks and Barlow [9]; unfortunately, publication of this most useful collection of information had to be abandoned for financial reasons after the appearance of three volumes covering the years 1969 - 74 inclusive [9, 10]. In parallel with early volumes of *Fluorine Chemistry* and *Advances in Fluorine Chemistry*, important aids to practicing organofluorine chemists appeared in the form of the immensely useful and exhaustive treatises *Aliphatic Fluorine Compounds*, by Lovelace, Rausch and Postelnek [11] and *Aromatic Fluorine Compounds*, by Pavlath and Leffler [12]. Unfortunately, it is now beyond human capability to assemble such structured catalogs of data for all fluorinated compounds, of which there are some 440 000 according to a recent census conducted by the American Chemical Abstracts Service (August 2, 1985). Hopefully, critical monographs and reviews will cover the ever-increasing primary literature (currently about 6 000 papers and patents a year) on theoretical, preparative and applied aspects of fluorine compounds. Three such monographs already available can be labeled as textbooks as well: Sheppard and Sharts' *Organic Fluorine Chemistry* [13], Chambers' *Fluorine in Organic Chemistry* [14], and Hudlický's *Chemistry of Organic Fluorine Compounds* [15]. The last (903 pp.) emphasizes laboratory aspects, and contains selected procedures of preparative and analytical natures. Preparative chemistry has been thoroughly covered by Forche, Hahn and Stroh in the first half (500 pages) of Vol. V/3 of Houben-Weyl's *Methoden der Organischen Chemie* [16] (actual laboratory procedures are described). More specialized laboratory applications are described in several reviews in *Organic Reactions* (see 'Aliphatic Fluorine Compounds' by Henne [17], and 'The Schiemann Reaction' by Roe [18]), Vol. 21 [19] of which is totally devoted to synthetic applications of sulfur tetrafluoride (by Boswell *et al.*) and to selective methods for the preparation of monofluoroaliphatic compounds (by Sharts and Sheppard). A similar treatment of aminofluorosulfuranes (*e.g.* DAST, Et_2NSF_3) as fluorinating agents will appear in the same series in the near future. A two-volume Russian laboratory manual which covers more than 500 preparative procedures is available (*Sintezy Ftororganicheskih Soedinenii*, edited by Knunyants and Yakobson), and a collection of the most interesting of these (dealing mainly with per- and poly-fluorinated compounds) has been published in English recently [20]. A very thorough survey in German of the chemistry and applications of cyclic organofluorine compounds is to be found in *Chemie und Technologie Cyclischer Fluorverbindungen* by Schiemann and Cornils [21]. The utmost importance of ^{19}F NMR spectroscopy to the practising fluorine chemist is reflected in the compilations of data available (see p. 291) [22 - 25].

A few monographs are highly specialized, dealing with fairly narrow topics: Rudge's *The Manufacture and Use of Fluorine and its Compounds* [26], Wall's *Fluoropolymers* [27], Stephen and Little's *Halothane (Fluothane)* [dealing with the most widely-used inhalation anesthetic (see p. 364)] [28]. Emeléus' *Fluorine and its Compounds* [29], Banks' *Fluorocarbons and their Derivatives* [30], Scherer's *Technische Organische Fluorchemie* [31], Osteroth's *Chemie und Technologie Aliphatischer Fluororganischen Verbindungen* [32], Saunder's *Phosphorus and Fluorine* [33] and Pattison's *Toxic Aliphatic Fluorine Compounds* [34].

For keeping up-to-date on applied organic fluorine chemistry readers should consult two recent books edited by Banks: *Organofluorine Chemicals and their Industrial Applications* [35] and *Preparation, Properties, and Industrial Applications of Organofluorine Compounds* [36]. The ever increasing role of organofluorine compounds in medicine and pharmacology is revealed not only in these two volumes, but in *Biochemistry Involving Carbon–Fluorine Bonds* [37] and *Biomedical Aspects of Fluorine Chemistry* [38] edited by Filler, and by Filler and Kobayashi, respectively.

In addition to monographs and articles in *Organic Reactions* [17 - 19] countless reviews of interest to the organofluorine chemist exist. A critical selection was assembled by Sheppard and Sharts [13] and since then many more than can be mentioned here have been published in numerous languages.

A recent 'Patai' contains an update on the synthesis of organofluorine compounds by Hudlický and Hudlický [39a], a review on fluorinations with xenon fluorides by Zupan [39b] and a chapter on fluorocarbons by Smart [39c]. Aliphatic fluorine compounds have been reviewed by Woodfine [40] and by Liebig and Ulm [41]. Synthesis of polyfluoroaromatic compounds formed the subject of a review by Yakobson and Vlasov [42] and the chemistry of polyfluoroheteroaromatics one by Chambers and Sargent [43]. Syntheses of ^{18}F-containing compounds, which are of increasing interest (see p. 371), have been described by Palmer, Clark and Goulding [44], and by Tewson [45]. Of a more specialized nature are reviews by Rozen and Filler [46] on α-fluorinated carbonyl compounds, by Stang *et al.* on the chemistry of trifluoromethanesulfonic acid and its derivatives [47 - 50], by Kobayashi and Kumadaki on valence bond isomers of aromatic trifluoromethyl compounds [51], and by Stock and Wasielewski on carbon–fluorine hyperconjugation [52].

A very good source of review articles on many aspects of fluorine chemistry is the Russian journal *Uspekhi Khimii* (translated into English as *Russian Chemical Reviews*). Examples include reviews on perfluoromethacrylic acid derivatives by Rokhlin *et al.* [53a], on the perfluoro-t-butyl anion by Dyatkin *et al.* [53b], on fluorinated ketenimines by Gambaryan [53c], on *N*-fluoroimides by Fokin *et al.* [53d], on fluorinated β-diketones by Pashkevich *et al.* [53e], on fluorinated halomethylene phosphoranes and ylides by Tyuleneva *et al.* [53f], on aliphatic nitroso compounds by Knunyants *et al.* [53g], on fluorinated dyes by Yagupolsky *et al.* [53h] and on perfluoroisobutylene by Zeifman *et al.* [53i].

References

1 H. Moissan, *Le fluor et ses composés,* Steinheil, Paris, 1900.

2 (a) O. Ruff, *Die Chemie des Fluors,* J. Springer, Berlin, 1920.
(b) W. Bockemüller, *Organische Fluorverbindungen,* Enke, Stuttgart, 1936.

3 E. T. McBee (ed.), *Ind. Eng. Chem., 39* (1947) 236; see also *Anal. Chem., 19* (1947) 146 and 193.

4 C. Slesser and S. R. Schram (eds.), *Preparation, Properties and Technology of Fluorine and Organic Fluoro Compounds,* McGraw-Hill, New York, 1951.

5 J. H. Simons (ed.), *Fluorine Chemistry,* Academic, New York: (a) Vol. I, 1950; (b) Vol. II, 1954; (c) Vol. III, 1963; (d) Vol. IV, 1965; (e) Vol. V, 1964.

6 M. Stacey, J. C. Tatlow and A. G. Sharpe (eds.), *Advances in Fluorine Chemistry,* Butterworth, London: (a) Vol. 1, 1960; (b) Vol. 2, 1961; (c) Vol. 3, 1963; (d) Vol. 4, 1965; (e) Vol. 5, 1965.

7 J. C. Tatlow, R. D. Peacock, H. H. Hyman and M. Stacey (eds.), *Advances in Fluorine Chemistry,* Butterworth, London; Chemical Rubber Company, Cleveland, OH, U.S.A.: (a) Vol. 6, 1970; (b) Vol. 7, 1973.

8 P. Tarrant (ed.), *Fluorine Chemistry Reviews,* Dekker, New York: (a) Vol. 1, 1967; (b) Vol. 2, 1968; (c) Vol. 3, 1969; (d) Vol. 4, 1969; (e) Vol. 5, 1971; (f) Vol. 6, 1973; (g) Vol. 7, 1974; (h) Vol. 8, 1977.

9 R. E. Banks and M. G. Barlow (eds.), *Fluorocarbon and Related Chemistry*, Vol. 1, The Chemical Society, London, 1971.

10 R. E. Banks and M. G. Barlow (eds.), *Fluorocarbon and Related Chemistry*, The Chemical Society, London: (a) Vol. 2, 1974; (b) Vol. 3, 1976.

11 A. M. Lovelace, D. A. Rausch and W. Postelnek, *Aliphatic Fluorine Compounds*, Reinhold, New York, 1958.

12 A. E. Pavlath and A. L. Leffler, *Aromatic Fluorine Compounds*, Reinhold, New York, 1962.

13 W. A. Sheppard and C. M. Sharts, *Organic Fluorine Chemistry*, Benjamin, New York, 1969.

14 R. D. Chambers, *Fluorine in Organic Chemistry*, Wiley, New York, 1973.

15 M. Hudlický, *Chemistry of Organic Fluorine Compounds*, Pergamon, Oxford, 1961; McMillan, New York, 1962; 2nd Ed., Ellis Horwood, Chichester, 1976.

16 E. Forche, W. Hahn and R. Stroh, in Houben, Weyl and Müller (eds.), *Methoden der Organischen Chemie*, Vol. V/3, *Fluor und Chlor*, G. Thieme, Stuttgart, 1962.

17 A. L. Henne, *Org. React.*, *2* (1944) 49.

18 A. Roe, *Org. React.*, *5* (1949) 193.

19 (a) G. A. Boswell, W. C. Ripka, R. M. Scribner and C. W. Tullock, *Org. React.*, *21* (1974) 1; (b) C. M. Sharts and W. A. Sheppard, *ibid.*, *21* (1974) 125.

20 I. L. Knunyants and G. G. Yakobson, *Sintezy Ftororganicheskih Soedinenii* (in Russian), Khimia, Moscow, 1973; I. L. Knunyants and G. G. Yakobson (eds.), *Synthesis of Fluoroorganic Compounds*, Springer-Verlag, Berlin, 1985.

21 G. Schiemann and B. Cornils, *Chemie und Technologie Cyclischer Fluorbindungen*, Enke, Stuttgart, 1969.

22 C. H. Dungan and J. R. Van Wazer, *Compilation of Reported* ^{19}*F NMR Shifts, 1951 - 1967*, Wiley-Interscience, New York, 1970.

23 J. W. Emsley and L. Phillips, *Prog. Nucl. Magn. Reson. Spectrosc.*, *7* (1971) 1.

24 (a) V. Wray, *Annu. Rep. NMR Spectrosc.*, *10B* (1980) ; (b) V. Wray, *ibid.*, *14* (1983).

25 J. W. Emsley, L. Phillips and V. Wray, *Fluorine Coupling Constants*, Pergamon, Oxford, 1977.

26 A. J. Rudge, *The Manufacture and Use of Fluorine and its Compounds*, Oxford University Press, Oxford, 1962.

27 L. A. Wall (ed.), *Fluoropolymers*, Wiley-Interscience, New York, 1973.

28 C. R. Stephen and D. M. Little, Jr., *Halothane (Fluothane)*, The Williams and Wilkins Co., Baltimore, 1961.

29 H. J. Emeléus, *The Chemistry of Fluorine and Its Compounds*, Academic, New York, 1969.

30 R. E. Banks, *Fluorocarbons and Their Derivatives*, Oldbourne, London, 1964 (2nd Ed., Macdonald, London, 1970).

31 O. Scherer, *Top. Curr. Chem.*, *14* (1970).

32 D. Osteroth, *Chemie und Technologie Aliphatischer Fluororganischen Verbindungen*, Enke, Stuttgart, 1964.

33 B. C. Saunders, *Phosphorus and Fluorine. The Chemistry and Toxic Action of Their Organic Compounds*, Cambridge University Press, Cambridge, 1957.

34 F. L. M. Pattison, *Toxic Aliphatic Fluorine Compounds*, Elsevier, Amsterdam, 1959.

35 R. E. Banks (ed.), *Organofluorine Chemicals and Their Industrial Applications*, Ellis Horwood, Chichester, 1979.

36 R. E. Banks (ed.), *Preparation, Properties, and Industrial Applications of Organofluorine Compounds*, Ellis Horwood, Chichester, 1982.

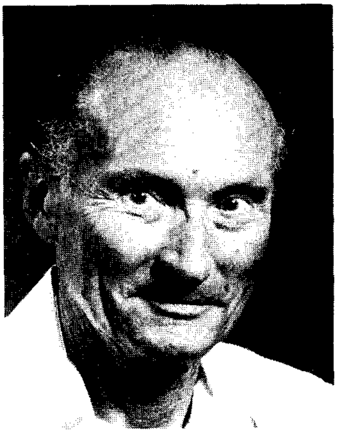
37 R. Filler, *Biochemistry Involving Carbon–Fluorine Bonds*, American Chemical Society, Washington DC, 1976.

38 R. Filler and Y. Kobayashi, *Biomedical Aspects of Fluorine Chemistry*, Elsevier Biomedical Press, Amsterdam, 1982.

39 (a) H. Hudlický and T. Hudlický, in S. Patai and Z. Rappoport (eds.), *The Chemistry of Functional Groups*, Suppl. D, *Formation of Carbon–Halogen Bonds*, Wiley, Chichester, 1983, p. 1021; (b) M. Zupan, *ibid.*, p. 657; (c) B. E. Smart, *ibid.*, p. 603.
40 H. Woodfine, *Chim. Ind., Genie Chim.*, *101* (1969) 612, 895.
41 H. Liebig and K. Ulm, *Chem.-Ztg.*, *99* (1975) 477; *ibid.*, *100* (1976) 3.
42 G. G. Yakobson and V. M. Vlasov, *Synthesis*, (1976) 652.
43 R. D. Chambers and C. R. Sargent, *Adv. Heterocycl. Chem.*, *28* (1981) 1.
44 A. J. Palmer, J. C. Clark and R. W. Goulding, *Int. J. Appl. Radiat. Isot.*, *28* (1977) 53.
45 T. J. Tewson, *Appl. Nucl. Radiochem.*, (1982) 163.
46 S. Rozen and R. Filler, *Tetrahedron*, *41* (1985) 1111.
47 P. J. Stang, M. Hanack and L. R. Subramanian, *Synthesis*, (1982) 85.
48 P. J. Stang, *Acc. Chem. Res.*, *11* (1978) 107.
49 J. B. Hendrickson, D. D. Sternbach and K. W. Bair, *Acc. Chem. Res.*, *10* (1977) 306.
50 J. B. Hendrickson, K. W. Bair, R. Bergeron, A. Giga, P. L. Skipper, D. D. Sternbach and J. A. Wareing, *Org. Prep. Proced. Int.*, *9* (1979) 173.
51 Y. Kobayashi and I. Kumadaki, *Acc. Chem. Res.*, *14* (1981) 76.
52 L. M. Stock and M. R. Wasielewski, *Prog. Phys. Org. Chem.*, *13* (1981) 253.
53 (a) E. M. Rokhlin, E. G. Abduganiev and V. Utebaev, *Usp. Khim.*, *45* (1976) 1177 (Engl. Transl., p. 593); (b) B. L. Dyatkin, N. I. Delyagina and S. R. Sterlin, *ibid.*, *45* (1976) 1205 (Engl. Transl., p. 607); (c) N. P. Gambaryan, *ibid.*, *45* (1976) 1251 (Engl. Transl., p. 630); (d) A. V. Fokin, A. T. Uzun and V. P. Stolyarov, *ibid.*, *46* (1977) 1995 (Engl. Transl., p. 1057); (e) K. I. Pashkevich, V. I. Salantin and I. Y. Postovskii, *ibid.*, *50* (1981) 325 (Engl. Transl., p. 180); (f) V. V. Tyuleneva, E. M. Rokhlin and I. L. Knunyants, *ibid.*, *50* (1981) 522 (Engl. Transl., p. 280); *ibid.*, *51* (1982) 3 (Engl. Transl., p. 1); (g) I. L. Knunyants, Y. A. Sizov and O. V. Ukharov, *ibid.*, *52* (1983) 976 (Engl. Transl., p. 554); (h) L. M. Yagupolskii, A. Y. Ilchenko and L. Z. Gandelsman, *ibid.*, *52* (1983) 1732 (Engl. Transl., p. 993); (i) Y. V. Zeifman, E. G. Ter-Gabrielyan, N. P. Gambaryan and I. L. Knunyants, *ibid.*, *53* (1984) 431 (Engl. Transl., p. 256).

BIOGRAPHIC NOTE

Miloš Hudlický was born in Czechoslovakia in 1919 and studied chemistry at the Prague Institute of Technology. During World War II he was employed at the Synthetic Rubber Research Institute in Zlin, returning to Prague to complete his Ph.D. studies (1946) and eventually to join the staff of the Institute of Technology, where he rose to the rank of Associate Professor (1954). He spent 10 years (1958 - 68) at the Research Institute of Pharmacy and Biochemistry in Prague before moving to a professorial position in Virginia.



M. Hudlický

Appendix 11.7

Perfluoroalkyl iodides

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Scientific effort in the early 1940s was concentrated on the preparation of fluorocarbons, and the possibility of making fluorocarbon derivatives R_FX, where the R_F is a perfluoroalkyl group and X a functional group such as CO_2H or SO_3H, by the techniques then available was remote.

The synthesis of the first perfluoroalkyl iodide, CF_3I, in Cambridge, England in 1948 by the route

$$CI_4 \xrightarrow{IF_5} CF_3I$$

provided a compound with a reactive functional group and a key to the locked scientific door. The scientific discoveries that lay beyond that door have been rich indeed, and a vast range of fluorocarbon derivatives and perfluoroalkyl organometallics and organometalloids of industrial as well as academic importance have ensued.

The original route to CF_3I was difficult and dangerous and is no longer used, but it provided sufficient material to enable the basic chemistry to be explored. The carbon–iodine bond in CF_3I can be broken homolytically by heat (200 °C) or light of wavelength < 3000 Å, and examples of early syntheses are:

$$CF_3I \left\{ \begin{array}{l} \xrightarrow{Hg} CF_3HgI \longrightarrow Hg(CF_3)_2 \\ \xrightarrow{P} (CF_3)_3P,\ (CF_3)_2PI,\ CF_3PI_2 \\ \xrightarrow{S} CF_3SSCF_3 \\ \xrightarrow{NO} CF_3NO \end{array} \right.$$

Of special importance was the discovery that CF_3I reacted by addition with olefinic or acetylenic compounds, *e.g.*,

$$CF_3I \left\{ \begin{array}{l} \xrightarrow{C_2H_4} CF_3CH_2CH_2I \\ \xrightarrow{C_2F_4} CF_3[CF_2CF_2]_nI \\ \xrightarrow{CF_2=CFCl} CF_3[CF_2CFCl]_nI \\ \xrightarrow{CH_2=CHCH_2OH} CF_3CH_2CHICH_2OH \\ \xrightarrow{C_2H_2} CF_3CH=CHI \end{array} \right.$$

by the free-radical pathway known as telomerisation, *e.g.*

$$\begin{tikzcd}
CF_3I \arrow[r] & CF_3\cdot \arrow[r, "C_2F_4"] & CF_3CF_2CF_2\cdot \arrow[r, "C_2F_4"] \arrow[d, "CF_3I"] & CF_3CF_2CF_2CF_2CF_2\cdot \arrow[r, "C_2F_4"] \arrow[d, "CF_3I"] & \text{etc.} \\
 & & CF_3CF_2CF_2I & CF_3(CF_2)_4I &
\end{tikzcd}$$

An olefin such as ethylene which does not readily undergo free-radical polymerisation at room temperature gives an almost quantitative yield of the 1:1 adduct $CF_3CH_2CH_2I$, whereas with C_2F_4, an olefin which polymerises readily, choice of reactant ratios and temperature provide the main control for the value of n in the telomer $CF_3[CF_2CF_2]_nI$. The long-chain fluorocarbon iodides provided a fluorocarbon chain with a functional end-group which reacts chemically like CF_3I itself. The synthesis of a wide array of fluorocarbon derivatives became possible, *e.g.*

$$CF_3CH_2CH_2I \xrightarrow{-HI} CF_3CH{=}CH_2$$

$$\begin{tikzcd}
CF_3[CF_2CF_2]_nI \arrow[r, "C_2H_4"] & CF_3[CF_2CF_2]_nCH_2CH_2I \arrow[r] & CF_3[CF_2CF_2]_nCH{=}CH_2 \arrow[d, "\text{oxidation}"] \\
 & & CF_3[CF_2CF_2]_nCO_2H
\end{tikzcd}$$

$$CF_3CF_2CF_2I \xrightarrow{SO_3} C_2F_5CO_2H$$

$$CF_3PI_2 \xrightarrow[\text{(ii) oxidation}]{\text{(i) } H_2O} CF_3PO(OH)_2$$

$$CF_3SSCF_3 \xrightarrow{Cl_2} CF_3SCl \longrightarrow CF_3SO_3H$$

Two important alternative routes to polyfluoroalkyl iodides soon followed from further work at Cambridge and later Manchester, *e.g.*,

Route (a)

$$C_2F_4 \xrightarrow{ICl} CF_2ClCF_2I$$

$$C_2F_4 \xrightarrow{I_2} CF_2ICF_2I \xrightarrow{C_2F_4} I[CF_2CF_2]_nI$$

$$C_2F_4 \xrightarrow{IF_5} CF_3CF_2I$$

$$CF_2{=}CFCl \xrightarrow{ICl} CF_2ClCFClI$$

Compounds with a carbon–iodine bond are readily cleaved homolytically. Thus, commercially available tetrafluoroethylene gave C_2F_5I, while hexafluoropropene gave $(CF_3)_2CFI$, now the perfluoroalkyl iodides of choice for industrial processes.

Route (b)

$$CH_3(CH_2)_nCOF \xrightarrow[\text{fluorination}]{\text{electrochem.}} CF_3(CF_2)_nCOF$$

$$CF_3(CF_2)_nCO_2H \longrightarrow \underset{\text{(anhydrous)}}{CF_3(CF_2)_nCO_2Ag} \xrightarrow[\text{heat}]{I_2} CF_3(CF_2)_nI$$

Development of the unique and important method of electrochemical fluorination by J. H. Simons and the 3M Corp. has enabled a number of fluorocarbon acids to be prepared on a laboratory or industrial scale.

Electrochemical fluorination provides one major route to the perfluoroalkane carboxylic and sulphonic acids from which industrially relevant surfactants, fire-extinguishing chemicals, textile treatment formulations, etc. stem. An equally important industrial route to the precursors of such materials uses tetrafluoroethylene to build up the chain.

$$C_2F_4 \longrightarrow CF_3CF_2I \xrightarrow{C_2F_4} C_2F_5[CF_2CF_2]_nI \longrightarrow C_2F_5[CF_2CF_2]_nCH_2CH_2X$$

where, for example, $n = 3$ when $X = OH, CO_2H, SO_3H, NR_2$.

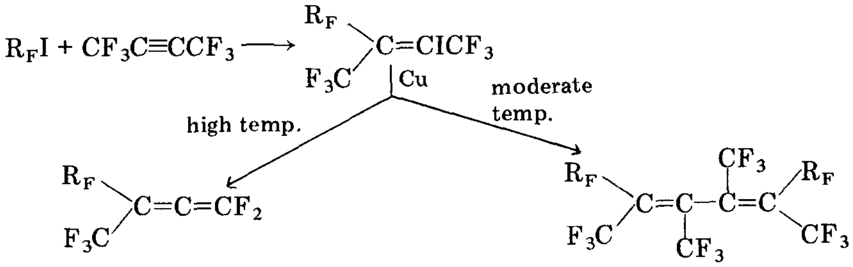
Many new organofluorine compounds have arisen from the fluorocarbon iodides, *e.g.*,

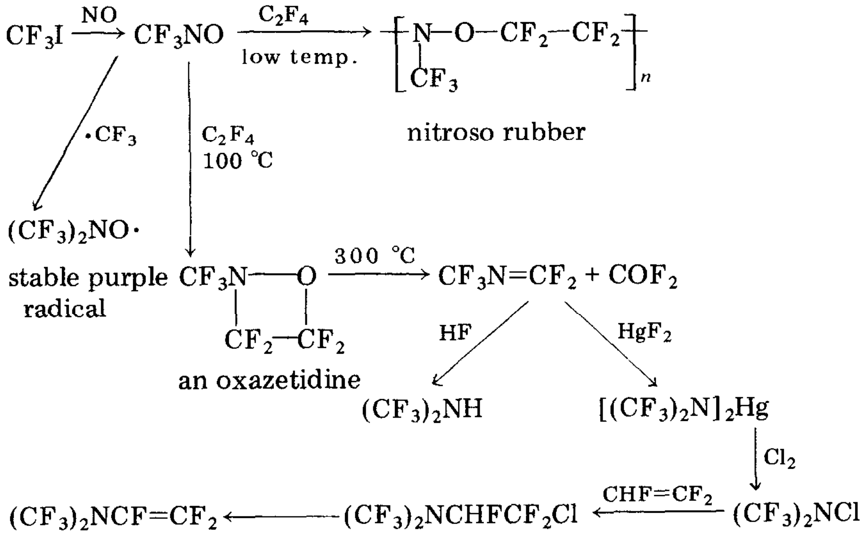
$$CF_3I \xrightarrow{C_2H_2} CF_3CH{=}CHI \xrightarrow{-HI} CF_3C{\equiv}CH$$

$$CF_3I \xrightarrow{CH_2=C=CH_2} CF_3CH_2CI{=}CH_2 \longrightarrow CF_3CH{=}C{=}CH_2$$

$$\begin{tikzcd}
CF_3I + CF_2{=}CFCl \arrow[r] & CF_3CF_2CFClI \arrow[r, "CH_2=CF_2"] & CF_3CF_2CFClCH_2CF_2I \arrow[d] \\
 & & CF_3CF_2CF{=}C{=}CF_2
\end{tikzcd}$$

$$\begin{tikzcd}
CF_2{=}CFCl \arrow[r] & CF_2ClCFClI \arrow[r, "Zn", "\text{(couple)}"'] \arrow[d, "C_2H_4"] & CF_2ClCFClCFClCF_2Cl \arrow[d, "\text{Zn (dechlorinate)}"] \\
 & CF_2ClCFClCH_2CH_2I \arrow[d] & CF_2{=}CFCF{=}CF_2 \\
 & CF_2{=}CFCH{=}CH_2 &
\end{tikzcd}$$





$$\begin{tikzcd}
CF_3I \arrow[r] & CF_3CH{=}CH_2 \arrow[r, "MeSiHCl_2"] & CF_3CH_2CH_2SiMeCl_2 \arrow[d, "H_2O"] \\
 & & \text{fluorosilicone polymer}
\end{tikzcd}$$

$$C_3F_7I + ArI \xrightarrow{Cu} ArC_3F_7$$

$$CF_3I \longrightarrow CF_3HgI \xrightarrow{I^-} CF_3^- \xrightarrow{-F} \ddot{C}F_2$$

difluorocarbene

It was soon appreciated that nucleophilic attack on a perfluoroalkyl iodide usually occurs on iodine rather than carbon:

$$R_FI \xrightarrow{OH^-} R_F^- \xrightarrow{solvent} R_FH$$

and this can be utilised in a route to perfluoroalkanesulphonic acids:

$$\begin{tikzcd}
R_FI \arrow[r, "MeS^-"] & R_F^- \; (+\, MeSI \longrightarrow Me_2S_2 + I_2) \arrow[d, "Me_2S_2"] & \\
& R_FSMe + MeS^- \arrow[r, "R_FI"] \arrow[d, "\text{oxidation}"] & \text{etc.} \\
& R_FSO_3H &
\end{tikzcd}$$

The possibility of synthesising an organometallic compound via ionic or radical–ionic reactions of a solution of a perfluoroalkyl iodide with a metal was a natural counterpart to the synthesis of an organometalloidal compound by a gas phase (probably free radical), thermal or photochemical route. Early attempts were only moderately successful, and whilst a Grignard compound is slowly formed it readily undergoes α-elimination,

$$\begin{tikzcd}
CF_3I + Mg \arrow[r, "THF", "\text{slow}"'] & CF_3MgI \arrow[r] \arrow[dl, "H_2O"'] \arrow[dr, "CO_2"] & \ddot{C}F_2 \\
CHF_3 & & CF_3CO_2H
\end{tikzcd}$$

as do lithium or magnesium compounds prepared by exchange reactions.

$$\begin{tikzcd}
n\text{-}C_3F_7I + BuLi \arrow[r, "Et_2O", "-78\ ^\circ C"'] & n\text{-}C_3F_7Li \arrow[r] \arrow[d, "RCHO"] & C_3F_6 \\
& C_3F_7CH(OH)R &
\end{tikzcd}$$

$$n\text{-}C_3F_7I + PhMgBr \xrightarrow{-78\ ^\circ C} C_3F_7MgBr \longrightarrow C_3F_6$$

$$C_2F_5I + Me_2SnCl_2 \xrightarrow[THF]{Mg} (C_2F_5)_2SnMe_2$$

$$CF_2{=}CFI \xrightarrow[Et_2O]{Mg} CF_2{=}CFMgI \xrightarrow{SiCl_4} Si(CF{=}CF_2)_4$$

Perfluoroalkyl magnesium and lithium compounds are thus best generated in the presence of a reactant such as RCHO or RCOCl, but even this approach gives only modest yields, and alternative routes to the desired final product without use of organometallic intermediates derived from electropositive metals are almost always available and are to be preferred. Yields are much better when more covalent organometallic compounds are involved, *e.g.*

$$CF_3I + GeI_2 \longrightarrow CF_3GeI + (CF_3)_2GeI_2$$

$$C_3F_7I + Me_3SnSnMe_3 \longrightarrow C_3F_7SnMe_3$$

$$C_2F_5I + PbMe_4 \longrightarrow C_2F_5PbMe_3$$

$$C_7F_{15}I + Cu \xrightarrow{DMF} [C_7F_{15}Cu] \xrightarrow{ArI} C_7F_{15}Ar$$

$$CF_2{=}CFI + C_6F_5Cu \xrightarrow{130\ ^\circ C} C_6F_5CF{=}CF_2$$

$$I(CF_2)_4I + Cu + PhI \longrightarrow Ph(CF_2)_4Ph$$

$$CF_3I + CpCo(CO)_2 \longrightarrow CpCo(CO)(CF_3)I$$

$$CF_3I + cis\text{-}PtMe_2L_2 \longrightarrow PtMe_2L_2(CF_3)I$$

(L = ligand)

$$CF_3I + SiF_2 \longrightarrow CF_3SiF_2I$$

The chemistry of the perfluoroalkyl iodides is now vast, and many research schools and industrial laboratories have contributed to its development in recent years. Detailed information about these versatile materials can be found in the several standard textbooks and reviews on organofluorine chemistry.

When a young research worker, the writer was inspired by the enthusiasm of Harry Emeléus and by the earlier work of two men. The elegant and accurate work of Fred Swarts, who prepared the first fluorocarbon derivative, CF_3CO_2H, amply demonstrated that organic fluorine chemistry had a potential at least as great as that of inorganic fluorine chemistry. Vision and mastery of technique was shown by Otto Ruff who made many new inorganic compounds. In their era the organic chemistry of fluorine was centred on compounds with one or sometimes two carbon atoms. The early work of Joe Simons and the subsequent work on direct and cobalt fluoride fluorination techniques showed that chains and rings of CF_2 groups could exist. The fluorocarbon iodides contributed much to the next stage of the developing saga — the preparation and use of fluorocarbon derivatives.

BIOGRAPHIC NOTE

Robert N. Haszeldine graduated at the University of Birmingham and then became an Assistant Director of Research at the University of Cambridge. He was Professor and Head of the Department of Chemistry at the University of Manchester Institute of Science and Technology from 1957 to 1976 and was Principal there during the period 1976 - 82. He has been awarded the Meldola Medal and the Corday-Morgan Medal and Prize and is a Fellow of the Royal Society. He has published around 500 papers, and has officiated as a consultant to many chemical companies throughout the world, and as a member of British Government Committees.

R. N. Haszeldine

Appendix 11.8

Perfluoropolyether fluids: properties and applications

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Perfluoropolyethers (PFPE) are a well-known class of fluids, in which the presence of the most electronegative atoms (O, F) bonded to C—C groups along the molecular chain assure high chemical and thermal stability and excellent physical properties (Table 8.1). Consequently PFPE fluids offer an unique combination of performances as lubricants which are highly reliable under very severe conditions.

TABLE 8.1

Properties shown by PFPE fluids

Chemical inertness	Non-flammability
Thermal resistance	Biological inertness
Resistance to oxidation	Good dielectric properties
Resistance to radiation	Good lubricating properties
High specific gravity	Low volatility
Low surface tension	Compatibility with plastics, elastomers and metals
Good viscostaticity	Solubility in perfluorinated organic solvents only
Low pour point	

Processes and products

Two processes are used to build, in one step, a PFPE chain:

(1) Anionic polymerisation of a perfluoro-olefin epoxide. The only process of this type used on an industrial scale utilises hexafluoropropene oxide as the feedstock [1].

(2) Direct perfluoro-olefin photo-oxidation. This more flexible process has been developed commercially by Montefluos to obtain several PFPE series with different structures and properties. Hexafluoropropene (HFP) and tetrafluoroethylene (TFE) have been the two main fluoro-olefins converted by photo-oxidation to PFPE chains [2, 3], but other compounds have been used successfully with this process (*e.g.* perfluorobutadiene [4]). Moreover, this process is the only one that can be oriented to obtain bifunctional PFPE derivatives [5]. Some information about the mechanisms and kinetics of the photo-oxidation process have been reported [6].

Both processes produce PFPE chains terminated, at one or both ends, with reactive groups, such as —C(O)F (acyl fluoride). The raw acidic materials are transformed into stable neutral oils in different ways, the most convenient procedure for obtaining oils with extreme chemical inertness being fluorination.

The proprietary fluorination technology owned by Montefluos allows neutral oils to be obtained in which hydrogen is not detectable (NMR spectroscopic sensitivity 0.1 ppm); this is by far the lowest level in comparison with other commercial PFPEs. In particular, by photo-oxidation of HFP and TFE, respectively, two PFPE families, namely Fomblin Y® and Fomblin Z® have been obtained (® = registered Trade Mark of Montedison):

$CF_3O(C_3F_6O)_p(CF_2O)_qCF_3$ *Fomblin Y*

$CF_3O(C_2F_4O)_m(CF_2O)_nCF_3$ *Fomblin Z*

The difluoromethylene groups are randomly sequenced in the chains. In the Fomblin Y chain the ratio q/p can vary between zero and 0.1, while in Fomblin Z the ratio m/n lies in the range 0.6 - 1.5; the average M.W. of a PFPE can be regulated between *ca.* 1000 and 40 000.

Properties and applications of Fomblin oils

A lot of work has been carried out in order to tailor suitable fractions for several applications. Table 8.2 shows typical physical properties of some Fomblin Y and Z fractions having different average molecular weights; a Fomblin Z possesses a higher average M.W. and viscosity index, and a lower vapour pressure and pour point than a Fomblin Y having the same viscosity. The data in Table 8.3 show that PFPE oils are resistant to a wide range of inorganic reagents and organic solvents; additionally, they are

TABLE 8.2

Physical properties of Fomblins

	HFP-PFPE			TFE-PFPE		
	Y 04	Y 25	Y R	Z 03	Z 15	Z 25
Average M.W. (VPO)	1500	2800	6000	4000	8500	10000
Kinematic viscosity/cSt at 20 °C	35	250	1500	35	150	250
Viscosity index	55	110	135	335	345	355
Specific gravity/g cm^{-3} at 20 °C	1.87	1.90	1.91	1.83	1.84	1.85
Pour point/°C	−70	−35	−25	−90	−75	−70
Volatility/% weight loss (ASTM D 971 24 h at 150 °C; flow N_2 = 2 l h^{-1})	60	7	1	13.3	4	0.025
Vapour pressure at 20 °C/Torr		2×10^{-5}			2×10^{-6}	2×10^{-12}
Surface tension/dyn cm^{-1}	19	20	21	22	23	24
Self ignition temp. (ASTM D 2155)	none	none	none	none	none	none
Electrical properties:						
Resistivity/Ω cm		10^{15}			4×10^{13}	
Dielectric strength/kV (100 mils)		40			35	
Dielectric constant at 20 °C (10^2 - 10^5 Hz)		2.15			2.01	
Dissipation loss at 20 °C (10^2 - 10^5 Hz)		4×10^{-4}			5×10^{-4}	

TABLE 8.3

Compatibility of PFPE with chemical agents, vulcanised rubbers and resins[a]

Agents	Conditions		Results
	Temperature	Notes	
Hydrogen halides			
HF, HCl, HBr	200 °C	1 l h^{-1}	unchanged[b]
Halogens			
Cl_2, Br_2, F_2	200 °C	1 l h^{-1}	unchanged
Non-metal halides			
BCl_3, $SbCl_3$	80 °C	5% (w/w)	unchanged
PBr_3, PCl_5	150 °C	5% (w/w)	unchanged
$SiCl_4$, $SiHCl_3$	150 °C	1 l h^{-1}	unchanged
Sulphur anhydrides			
SO_2, SO_3	200 °C	1 l h^{-1}	unchanged
Acid agents			
H_2SO_4 (98%)	70 °C	50% (w/w)	unchanged
Aqueous oxidisers			
$KMnO_4$ (6% w/w); $K_2Cr_2O_7$ (10% w/w)	70 °C	50% (w/w)	unchanged
Organic solvents			
Hydrocarbons, alcohols, ethers, esters, amides, ketones, acids	20 °C	50% (w/w)	insoluble
Vulcanised rubbers			
Natural rubber, SBR, NBR neoprene, EPDM	70 °C	ASTM D 471 166 h	retained tensile strength/elongation 95 - 105%
Plastomers			
PPO, PET, PBT, PST, PVC PEMD, PP, PPMA Nylon 66, polycarbonate	70 °C	*idem* 1000 h	retained tensile strength 100%

[a] Tests carried out on Y 25, Z 25.

[b] No significant change in acidity; viscosity change less than 5%.

compatible with commercial plastomers and elastomers. PFPE oils are thermally resistant up to about 270 - 300 °C, and the presence of oxygen does not affect this limit. The presence of catalysts or inhibitors can alter both ceiling temperature and rate of decomposition. Moreover, with metal catalysts the decomposition is affected by oxygen. Specific proprietary inhibitors have been developed to improve thermo-oxidative resistance of PFPE up to 320 °C, also in the presence of metals.

The data listed in Table 8.4 reveal the anti-wear properties of two Fomblin fluids of different classes, as measured with several test machines. The fluids show low values of wear and friction coefficient, but high mechanical resistance of the lubricant surface film. Consequently, Fomblins

TABLE 8.4

Anti-wear properties of PFPE

	Fomblin Z 25	Fomblin Y 25
Shell 4 ball wear		
ASTM D 2266 - 67		
1460 rpm, 40 kg, 1 h, 70 °C		
Average scar diam./mm	0.5	0.6
4 Ball E.P.		
I.P. 239		
1460 rpm, 10 s		
Welding load/kg	500	400
Reichert ring speed 1.7 m s^{-1}		
1.5 kg, 1 min.		
Average scar area/mm^2	4.0	4.1
Denison T 67 pin-on-disc		
static friction coeff.		
Stainless steel, speed/		
5×10^{-4} m s^{-1} at 20 °C	0.16	0.16
5×10^{-4} m s^{-1} at 200 °C	0.11	0.32
Dynamic friction coeff.		
2×10^{-2} m s^{-1} at 20 °C	0.15	0.13
2×10^{-2} m s^{-1} at 200 °C	0.11	0.15
0.2 m s^{-1} at 20 °C	0.08	0.10
0.2 m s^{-1} at 200 °C	0.08	0.13

also provide good lubrication at boundary conditions in systems where the moving mechanical parts of any materials are exposed to aggressive chemical environments and high temperatures. Long aging resistance can be assured; consequently the reliability of systems and maintenance costs are improved.

The PFPE fractions listed in Table 8.2 have conveniently large M.W. distributions. Many other grades have been produced via sophisticated fractionating operations in order to provide fractions with restricted M.W. distributions to use as working fluids in vacuum pumps and other systems (Fomblin Y-VAC; Table 8.5). The physical properties and chemical resistance of Fomblin Y VAC fluids allow them to be used as pump working fluids for vacuum systems where lack of contamination by fluid backstreaming, or the resistance to polymerisation or carbonisation, is absolutely essential, as in the production of high-quality materials for the electronics industry.

Special greases for use at extreme temperatures have been formulated by thickening several Fomblin fractions with PTFE and other agents or additives. In general, Fomblin greases show a good balance of anti-wear, physical properties and chemical inertness; moreover, they are not washed out by any solvent. They can be used over a very wide temperature range

TABLE 8.5

Fomblin Y-VAC fluid: typical properties and applications

Type Y-VAC series	Kin. visc./ cSt (20 °C) av. range	Kin. visc./ cSt (100 °C)	Mol. wt. (vpo)[a]	Vap. press./Torr (max value)[b]		Pour point/°C	Vacuum pump fields of application
				20 °C	100 °C		
06/6	60 - 66	4	1950	2×10^{-6}	5×10^{-3}	−50	turbomolecular, booster; lubrication under vacuum (UF_6)
18/8	180 - 200	8.5	2700	2×10^{-8}	2×10^{-4}	−42	turbomolecular, mechanical; ultraclean vacuum; diffusion; lubrication under vacuum (UF_6)
25/5	250 - 270	11	2850	2×10^{-6}	2×10^{-3}	−37	mechanical rotary pumps
25/9	270 - 290	11	2950	2×10^{-9}	2×10^{-5}	−35	diffusion pumps
40/11	400 - 500	19	3700	2×10^{-11}	5×10^{-7}	−32	lubrication under high vacuum (UF_6)
140/13	1400 - 1600	35 - 40	6500	5×10^{-13}	5×10^{-8}	−23	lubrication under high vacuum (UF_6)

[a] Vapour pressure osmometer method, solvent FC-75: number average value.

[b] Knudsen effusion method, thermogravimetric analyser Du Pont 951, vacuum 10^{-5} Torr.

(−70 °C to 220 °C, depending on their formulation) as sealants and lubricants (permanent also under high vacuum and temperature) for valves, packing glands, O-rings, bearings or gears and other systems with moving mechanical parts which come into contact with oxygen, other oxidising or aggressive gases, or hydrocarbon vapours. Their use provides protection from wear and corrosion, safety from explosion when using oxidisers and freedom from forward contamination.

Fields of application for Fomblin fluids and greases

Their high stability and good anti-wear properties make PFPE fluids and related greases suitable long-life lubricants for hostile environments. A general list of fields of application follows. The success of Fomblin fluids in so many different fields results from their unusual balance of properties that not only make them the solution to difficult technological problems but also minimise maintainance costs and assure long-life reliability.

Chemical industry

PFPE fluids are used as the working fluids for vacuum pumps (rotary, turbomolecular, vapour diffusion) and as lubricants for compressors and valves when aggressive gases are involved (*e.g.* liquid and gaseous oxygen, halogens, hydrogen halides, non-metal halides, sulphur dioxide).

Electronics industry

PFPE fluids are suitable as lubricants for mechanical vacuum pumps used in the manufacture of semiconductors by techniques such as plasma etching, LPCVD and ion implantation.

Electro-mechanical applications

PFPEs are successfully used to lubricate contactors, push-button switches and sliding electrical contacts where good lubrication and arc resistance are required.

Engineering fields

PFPEs are suitable for lubrication of high-temperature and chemically-resistant porous metal bearings, conveyor belts, paper and textile machinery. Plastic bearings show improved anti-wear behaviour when lubricated with PFPE.

Nuclear industries

PFPEs are the only fluids that have been approved as lubricant for ultracentrifuge bearings in UF_6 enrichment plants, where chemical resistance to UF_6 up to 130 °C and other stringent requirements, such as the absence of moisture and dust and very low vapour pressures, are necessary.

Aerospace projects

The combination of high viscostaticity, extremely low vapour pressure, low pour point and good E.P. lubricant properties without additives make the PFPE fluids particularly suitable for the aerospace industry — as lubricants for jet engines, space-exposed mechanisms and oxygen systems [4].

Magnetic recording media

Their low frictional coefficients, low volatilities and dielectric properties make PFPEs highly suitable for use with magnetic recording media, discs and tapes.

References

1 E. P. Moore, *U.S. Pat. 3 250 808* (1966); E. P. Moore, *U.S. Pat. 3 322 826* (1967).
2 D. Sianesi, A. Pasetti and C. Corti, *Br. Pat. 662 267* (1965); *U.S. Pat. 3 442 942* (1969).
3 D. Sianesi, A. Pasetti and G. Belardinelli, *Ital. Pats. 790 651* (1967) and *933 753* (1972); *U.S. Pats. 3 715 378* (1973) and *4 451 646* (1984).
4 D. Sianesi, G. Bernardi and A. Pasetti, *Ital. Pat. 745 275* (1965); G. Caporiccio, G. Viola and C. Corti, *Eur. Pat. 89 820* (1983).
5 D. Sianesi and G. Caporiccio, *Ital. Pat. 817 809* (1968); *U.S. Pat. 3 447 978* (1974).
6 D. Sianesi *et al.*, *Chim. Ind. (Milan)*, *55* (1973) 208.

BIOGRAPHIC NOTE

Gerardo Caporiccio joined Professor Natta's research group in 1959 after graduating from Milan University with a degree in industrial chemistry. In 1975 he became Head of Research and Development in Fluorine Chemistry for the Industrial Products Division of Montedison, and founded the Applied Science Activities section for PFPE and fluoropolymers. At present he is the Head of Basic and Applications Research on Fomblin® and new fluorinated materials in Montefluos.

G. Caporiccio

Appendix 11.9

High-yield reactions of elemental fluorine

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During the 18 years since breakthroughs were made by Lagow and Margrave [1, 2] in the laboratory use of elemental fluorine for organic direct fluorination, a very high and perhaps even surprising rate of progress has been maintained. As late as 1968 [3] it was written "use of fluorine for these reactions (addition to carbon–carbon double bonds and substitution of hydrogen) cannot be considered to be a useful general method. Fluorination by fluorine is unlikely to be used in normal laboratory organic syntheses". During the intervening years, however, not only have controlled reactions of elemental fluorine been applied to a very broad array of organic, inorganic and polymeric materials to produce fluorocarbons and fluorine compounds in the laboratory with yields often exceeding 90%, but work is currently underway on the scale-up of reactions. Although it is not widely known that this is the case, at least four major industrial firms in the United States and about the same number in Japan have under development pilot plants and projects designed to bring to the market complex organic and polymeric products based on controlled reactions of elemental fluorine.

Considering alternative exhaustive fluorination procedures, it should be remembered that the cobalt trifluoride process, which has been established for years industrially, requires elemental fluorine as a feedstock. It is also a high-temperature process which has associated with it the possibility of molecular rearrangements and serious limitations stemming from the fact that reactants must be vaporized at 200 - 300 °C in a reaction bed. While one might predict with confidence that elemental fluorination technology will render obsolete the cobalt trifluoride process over the next five years, it is certain that this broad technology will never supplant conventional C—F bond syntheses and telomerization of monomers, as practiced by industrial firms such as Du Pont and Montedison.

With production-scale yields often exceeding 90% and relatively little product purification required, elemental fluorination has a very good chance of competing favorably with the important Simons electrochemical fluorination process. From a basic point of view, the electrochemical process has little if any economic advantage since the cells are run at 6 - 7 V, and cells generating elemental fluorine from the same raw materials require similar voltages. Both processes, when reactions of hydrocarbons are involved, must generate 2 mol of fluorine atoms to incorporate one in the final product (half of the activated fluorine in each case ends up as hydrogen fluoride, which must be reactivated or recycled).

Laboratory achievements

In the laboratory (see Fig. 9.1), the aforementioned breakthrough concerning the solution of basic thermodynamic and kinetic problems associated with the extremely exothermic (potentially explosive) reactions of elemental fluorine has led to the generation of effective moderating techniques. Hence direct fluorination has at last become a generally applicable synthetic route in organic and organoelemental fluorine chemistry. That is not to say that there are not many fluorinated compounds made industrially at lower cost, but that for new synthetic targets, not already articles of commerce, the direct fluorination method may well be the one of choice, especially on the laboratory scale. A skilled chemist can usually deliver 5 - 10 g of an unknown perfluoro compound one to two months after it has been selected for synthesis, given the apparatus, of course.

The technique has developed to the point where one may now preserve '30 kcal bonds' (note, for example, the successful fluorination of alkyls such as hexamethyltungsten or tetramethylgermanium) or differentiate between, for example, six-coordinate sulfur or four-coordinate sulfur, or for that matter, five-coordinate phosphorus or three-coordinate phosphorus, by varying and carefully controlling the reaction conditions [4, 5].

Recently, high-yield syntheses of the first three perfluoro crown ethers (18-crown-6, 15-crown-5 and 12-crown-4) have been achieved [6]. These are thought to be important new biomaterials. Almost any hydrocarbon

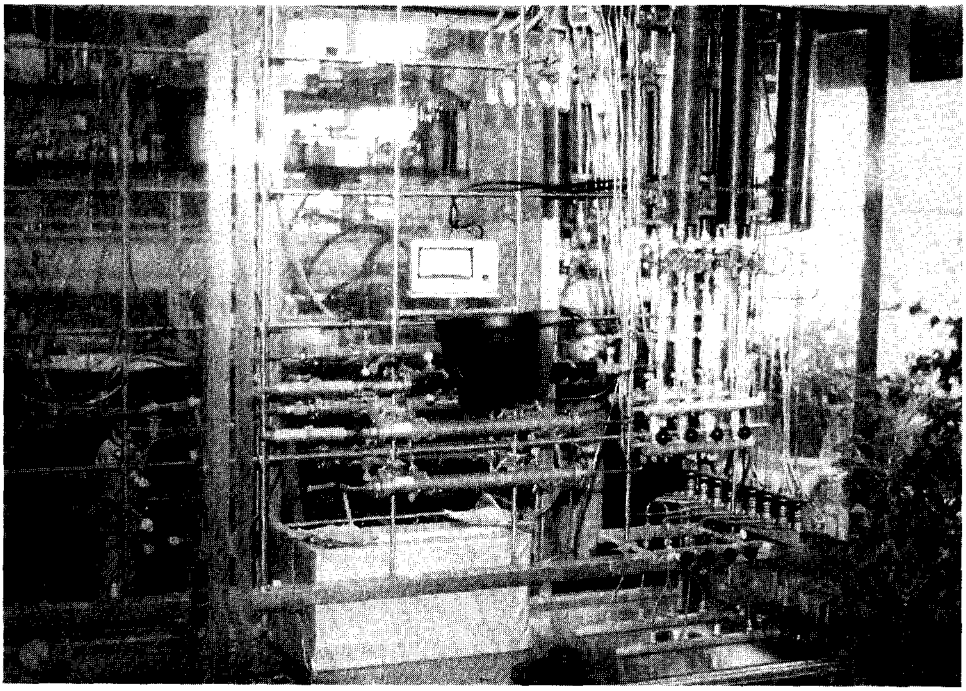

Fig. 9.1. Fluorine-handling apparatus and reactor systems.

species, even of the most unusual structure, can be converted easily to its fluorocarbon analog; for example, the fluorination of adamantane, norbornane, cyclo-octane, neopentane and many others have been demonstrated in yields that now exceed 90% [7]. Inorganic compounds are handled equally well; examples include carboranes, borazine, boron hydrides and many classes of organometallics. Soon to be reported are successful fluorinations of multiple metal–metal bonded compounds.

The best known aspect, and the first one to find commercialization in the direct fluorination area, was the fluorination of polymer surfaces and also complete conversion of hydrocarbon to fluorocarbon polymers [8]. This Lagow–Margrave invention, trademarked ‘Fluorokote’, involved many types of polymeric material in various forms — poly(ethylene) bottles, poly(propylene) objects, rubber gloves, etc. Poly(ethylene) bottles are easily given fluorocarbon surfaces (>0.1 mm), and this has been commercialized. Air Products have at least 20 licensees for what is known as their ‘Airo Pak process’ and Union Carbide has a ‘Linde fluorination’ process as well. Applications in chemical storage, pharmaceutical storage and cosmetic storage are widespread, and this process will soon enter the food industry. Complete fluorination of numerous polymers has been studied in the author’s research program. Work on perfluoropolyethers and two categories of fluorocarbon elastomers is nearing commercialization. In the simple cases of poly(ethylene), poly(propylene) and poly(styrene), conversion into fluorocarbon analogs occurs if the powder size is kept below 100 mesh.

The first successful fluorination in high yield of oxygen-containing hydrocarbon substrates of numerous types (ethers, esters, acids, etc.) were reported in the early 1970s [9, 10]. One of the most successful aspects of this work has been the extension to the synthesis of perfluoropolyethers. Perfluoropolyethers which were first marketed by Du Pont under the name ‘Krytox’ and later by Montedison under the name ‘Fomblin Z’ are materials of prime importance in high-technology areas (*e.g.* aerospace developments, satellites and military space weapon systems). These companies start from perfluoroolefins, but we have found it possible to fluorinate preformed polyethers directly; the simplest example is the perfluorination of poly(ethylene oxide) to give materials with excellent properties:

$$\text{(}CH_2{-}CH_2O\text{)}_n \xrightarrow{F_2} \text{(}CF_2{-}CF_2O\text{)}_n \qquad \begin{array}{l} n = > 20\,000,\ \text{high-performance lubricants} \\ n = 1 - 3 \times 10^6,\ \text{high-performance elastomers} \end{array}$$

The established commercial products sell in the range of $100 to $400 per pound. The long liquid range of the Montedison material makes it essential for U.S. military and space efforts in lubrication applications where the Du Pont material fails. The Lagow laboratory and Exfluor Research Corporation have produced several materials with the excellent temperature–viscosity properties required. The fluorination reaction is so complete that one cannot observe protons with Fourier transform infrared or NMR spectroscopy. Not only have solid versions of at least 40 structures been prepared, but oils of many structures are available via the Lagow synthesis as well [11 - 14].

A new technique has recently been developed in the author's laboratory involving perfluorination of *linear polyesters*, followed by treatment of the polymeric product with *sulfur tetrafluoride*; the second step converts backbone carbonyl groups to CF_2, thus providing a perfluoropolyether [15]. This also has important ramifications where fluorocarbon surfactant production is concerned. The high-molecular-weight materials are novel elastomers, and the flexibility of the ether linkage (it acts like a hinge), which imparts the unusual lubricant properties, should confer excellent low-temperature properties. Cross-linking techniques will need to be developed.

In addition to the conversion of hydrocarbons to fluorocarbons with fluorine, there have been very interesting and potentially important developments in selective fluorination recently. This approach has been explored by a number of investigators (notably Merritt, Grakauskas, Ruppert, Barton, Hesse and Rosen) [16 - 38].

Other interesting and important applications of reactions involving elemental fluorine are in the fluorocarbon/biomedical area. Progress is being made not only in the oxygen carrier area but also in the field of very inert, implantable, prosthetic devices and materials [39 - 43]. In the fluorocarbon membrane area, elemental fluorine chemistry may also prove to have important applications [44 - 46]. A potentially important development involving highly-selective gas-separation membranes will be described in the literature in the near future [47].

References

1 R. J. Lagow and J. L. Margrave, *Proc. Natl. Acad. Sci. USA*, *67* (1970) 4, 8A.
2 R. J. Lagow and J. L. Margrave, *Prog. Inorg. Chem.*, *26* (1979) 161.
3 C. M. Sharts, *J. Chem. Educ.*, *45* (1968) 3.
4 E. K. S. Liu and R. J. Lagow, *J. Chem. Soc., Chem. Commun.*, (1977) 450.
5 J. A. Morrison and R. J. Lagow, *Inorg. Chem.*, *16* (1977) 2972.
6 W. H. Lin, W. I. Bailey, Jr. and R. J. Lagow, *J. Chem. Soc., Chem. Commun.*, (1985) 1350.
7 N. J. Maraschin, B. D. Catsikis, L. H. Davis, G. Jarvinen and R. J. Lagow, *J. Am. Chem. Soc.*, 97 (1975) 513.
8 R. J. Lagow and J. L. Margrave, *Polym. Lett.*, *12* (1974) 177.
9 J. L. Adcock, R. A. Beh and R. J. Lagow, *J. Org. Chem.*, *40* (1975) 3271.
10 J. L. Adcock and R. J. Lagow, *J. Am. Chem. Soc.*, *96* (1974) 7588.
11 G. E. Gerhardt and R. J. Lagow, *J. Chem. Soc., Chem. Commun.*, (1977) 259.
12 G. E. Gerhardt and R. J. Lagow, *J. Org. Chem.*, *43* (1978) 4505.
13 G. E. Gerhardt, E. T. Dumitru and R. J. Lagow, *J. Polym. Sci., Polym. Chem. Ed.*, *18* (1979) 157.
14 G. E. Gerhardt and R. J. Lagow, *J. Chem. Soc., Perkin Trans. 1*, (1981) 1321.
15 D. F. Persico, G. E. Gerhardt and R. J. Lagow, *J. Am. Chem. Soc.*, *107* (1985) 1197.
16 I. Ruppert and U. Bastian, *Angew. Chem. Int. Ed. Engl.*, *16* (1978) 718.

17 I. Ruppert and U. Bastian, *Angew. Chem. Int. Ed. Engl., 17* (1978) 214.
18 J. G. Moelman, J. J. Gleeves, J. W. Hudgens and J. D. McDonald, *J. Chem. Phys., 62* (1973) 4790; J. G. Moelman and J. D. McDonald, *J. Chem. Phys., 62* (1975) 3052, 3061.
19 H. W. Chang and D. W. Setser, *J. Chem. Phys., 58* (1973) 2298; W. H. Duewer and D. W. Setser, *ibid., 58* (1973) 2310; K. C. Kim and D. W. Setser, *J. Phys. Chem., 77* (1973) 2493, 2499.
20 K. C. Kim, D. W. Setzer and C. M. Bogan, *J. Chem. Phys., 60* (1974) 1837.
21 J. T. Muckerman, *J. Chem. Phys., 54* (1971) 1155.
22 R. F. Merritt and F. A. Johnson, *J. Org. Chem., 31* (1966) 1859.
23 R. F. Merritt and T. E. Stevens, *J. Am. Chem. Soc., 88* (1966) 1822.
24 R. F. Merritt, *J. Org. Chem., 31* (1966) 3871.
25 R. F. Merritt and F. A. Johnson, *J. Org. Chem., 32* (1967) 416.
26 R. F. Merritt, *J. Org. Chem., 32* (1967) 4124; R. F. Merritt, *J. Am. Chem. Soc., 89* (1967) 609.
27 W. T. Miller, J. O. Stoffer, G. Fuller and A. C. Currie, *J. Am. Chem. Soc., 86* (1964) 51.
28 A. Y. Yakubovich, S. M. Rozenshtein and U. A. Ginsberg, *U.S.S.R. Pat. 162 825* (1965).
29 A. Y. Yakubovich, U. A. Ginsberg, S. M. Rozenshtein and S. M. Smirnov, *U.S.S.R. Pat. 165 162* (1965).
30 M. J. Kamlet and H. G. Adolph, *J. Org. Chem., 33* (1968) 3073.
31 V. Grakauskas and K. Baum, *J. Org. Chem., 33* (1968) 3080.
32 V. Graskauskas, *J. Org. Chem., 34* (1969) 965.
33 P. D. Schuman, P. Tarrant, D. A. Warner and G. Westmoreland, *Chem. Eng. News, 49* (1971) 40; *U.S. Pat. 3 954 758* (1976).
34 D. H. R. Barton, R. H. Hesse, H. T. Toh and M. M. Pechet, *J. Org. Chem., 37* (1972) 329.
35 D. Cech and A. Holz, *Collect. Czech. Chem. Commun., 41* (1976) 3335.
36 T. Ido, C. N. Wan, J. S. Fowler and A. P. Wolf, *J. Org. Chem., 42* (1977) 13.
37 D. H. R. Barton, R. H. Hesse, R. E. Markwell, M. M. Pechet and H. T. Toh, *J. Am. Chem. Soc., 98* (1976) 3034.
38 D. Alker, D. H. R. Barton, R. H. Hesse, J. Lister-James, R. E. Markwell, M. M. Pechet, S. Rozen, T. Takeshita and H. T. Toh, *Nouv. J. Chim., 4* (1980) 239.
39 L. C. Clark, Jr., L. A. Shimp and R. J. Lagow, *U.S. Pat. 4 110 474* (1978).
40 L. A. Shimp, L. C. Clark, Jr. and R. J. Lagow, *U.S. Pat. 4 187 252* (1980).
41 L. A. Shimp and R. J. Lagow, *J. Org. Chem., 42* (1976) 3437.
42 G. Robertson, E. K. S. Liu and R. J. Lagow, *J. Org. Chem., 43* (1978) 4981.
43 E. K. S. Liu and R. J. Lagow, *J. Fluorine Chem., 13* (1979) 71.
44 J. L. Adcock, S. Inoue and R. J. Lagow, *J. Am. Chem. Soc., 100* (1978) 1948.
45 R. J. Lagow, *U.S. Pat. 4 076 916* (1978).
46 J. L. Adcock, S. Inoue and R. J. Lagow, *U.S. Pat. 4 144 374* (1979).
47 C. L. Kiplinger, D. F. Persico, D. R. Paul and R. J. Lagow, *J. Appl. Polym. Sci.*, in press.

BIOGRAPHIC NOTE

R. J. Lagow

Richard J. Lagow was born in 1945 in Albuquerque, New Mexico. He received his bachelor's degree from Rice University (Houston, Texas) in 1967 and his Ph.D. in 1969; his early interests in fluorine chemistry centred on the fluorination of graphite while he was an undergraduate researcher in the laboratory of John L. Margrave at Rice University in the early 1960s. He is currently engaged in research in the areas of polylithium organic compounds, organometallic chemistry, novel metal alkyls, metal vapour-free radical chemistry, fluorine chemistry, fluorocarbon polymers and inorganic polymers, xenon–carbon compounds, plasma chemistry, high-temperature chemistry, fluorocarbon biomedical chemistry and the chemistry of $Ca_5(OH)(PO_4)_3$ — tooth and bone chemistry. Professor Lagow was on the faculty of the Department of Chemistry, Massachusetts Institute of Technology, from 1969 to 1976 when he became Professor of Chemistry at The University of Texas at Austin.

Appendix 11.10

Aerosol direct fluorination: a developing synthesis technology and an entry level mechanistic tool

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The aerosol direct fluorination process is unique in that a heterogeneous reaction is carried out under gas-like conditions [1 - 4]. Reactant molecules adsorbed onto airborne particles of sodium fluoride are subjected to attack by gaseous elemental fluorine under conditions such that the temperature and fluorine concentration in the reactor are continuously changed as the particles traverse the length of the reactor. This results in optimum rates of reaction with minimal fragmentation of reactant structures. Initial reaction-limiting conditions necessary to control the high exothermicity of elemental fluorinations are gradually changed so as to provide the final, forcing conditions necessary to achieve perfluorination. Mechanistic interpretations of product distributions under controlled stoichiometric conditions are possible because of the unusually clean reactions.

Aerosol direct fluorination is a valuable approach from both the fundamental and the applied chemical points of view. From the applied viewpoint it provides a flow process which can be scaled up using presently available technology. It is both fluorine-efficient and capable of producing high yields of single products, especially perfluorinated products. The purities of many products collected directly from the reactor are as high as 98%. From the fundamental viewpoint the versatility of the process, the high degree of control of reaction parameters and the control of conditions at the molecular level in a solvent-less reaction medium permit a controlled, mechanistically significant, observation of the process called 'direct fluorination'.

Conceptually, the aerosol direct fluorination process is simplicity itself (see Fig. 10.1). A hydrocarbon vapor is adsorbed or condensed onto the surface of a large number of microscopic (17 Å) [2] sodium fluoride pre-aerosol nucleating particles in a helium (or nitrogen) carrier gas at low (—196 °C) temperatures. The particles are then carried into a low temperature (—78 °C to —40 °C) region of a tubular microporous walled (2 μm) reactor in which fluorine diffuses through the porous walls into the reactor stream. As the adsorbed molecules are fluorinated they are simultaneously carried down the tubular reactor into regions of higher fluorine concentration and higher temperatures, where they undergo higher degrees of fluorination. The fluorine concentration in a typical reaction reaches 2 - 5%

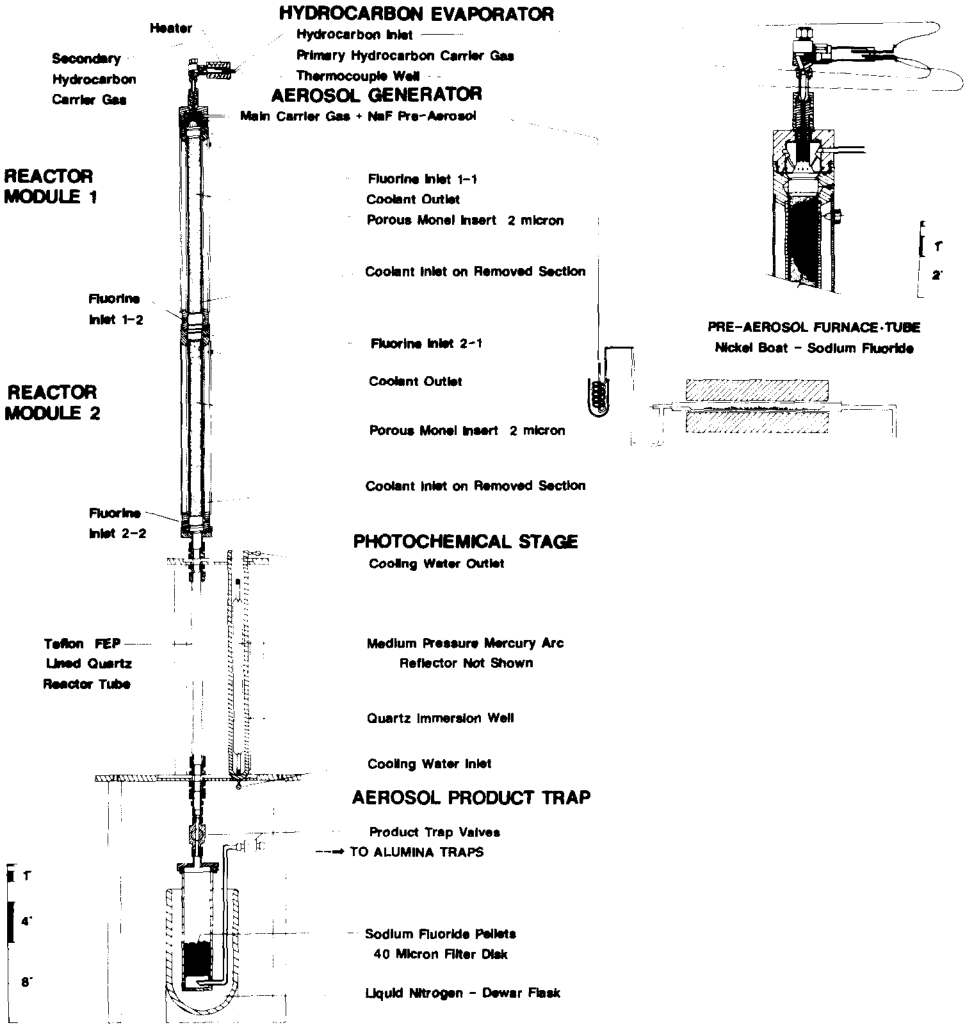


Fig. 10.1. Aerosol fluorinator.

by volume, which is usually calculated to be about twice the stoichiometrically required quantity. Molecules leaving the sub-ambient temperature region of the reactor are usually 40 - 60% fluorinated and are then introduced into a specially designed photochemical reactor. The photochemical reaction completes the fluorination by removing the very unreactive residual hydrogens through dissociation of molecular fluorine and producing, presumably by atomic fluorine attack, radicals which scavenge available molecular fluorine [3, 4]. Both phenomena result in virtually 100% perfluorination with minimal fragmentation of the carbon skeletons. The alternative to 'photo-chemical finishing' is to greatly increase the concentration of fluorine, which results in enormous (50X) stoichiometric excesses and greatly reduced efficiency of fluorine utilization if the fluorine is not recycled. For example, at 30% fluorine (a 48X stoichiometric excess) up to 90% fluorination with 10% perfluorination can be achieved in the subambient reactor. The entire fluorination process typically requires 0.5 - 1.5 min for a given unit particle to traverse the reactor.

The following process parameters can be varied semi-independently: reactor temperatures (gradients), fluorine concentrations (gradients), reaction or residence time, reaction stoichiometry, hydrocarbon throughputs and type of finishing. Since the process is a flow process it can be maintained at a steady state for any preset group of reaction parameters. The amounts of material produced thus depend on the reactor size (40 mmol h^{-1} for a 2.5-cm diameter reactor) and on the length of time the reactor is in operation. The maximum scale of this reactor has not been definitively established. At the present effluent density, the scale increases as the square of the radius. Convective mixing of reagents in larger diameters due to the reverse thermal gradient in the reactor should allow the density to increase as much as tenfold. Industrial feasibility is thus quite probable, especially for speciality chemicals if not commodities. Safety of operation — a major consideration in any direct fluorination apparatus — is a major advantage of the aerosol system. The reactor is a 'non-critical' system and cannot run uncontrolled. A 'runaway' reaction and explosion are virtually impossible if 'failsafe' devices are installed to shut off fluorine flow.

The aerosol fluorinator produces excellent yields of perfluorinated alkanes, ethers, ketals, alkyl chlorides, acyl fluorides (from acyl chlorides and fluorides or esters) and moderate yields of perfluorinated esters and ketones, including the highly-branched ketones $CF_3COC(CF_3)_3$ and $(CF_3)_2CFCF_2COC(CF_3)_2$, as well as the orthoesters perfluoro-tetramethyl and -ethylene orthocarbonate [1, 5 - 11].

The development of the aerosol fluorination device/process was the result of an appreciation of the explosive reactivity of fine carbonaceous dusts suspended in air. Materials of low reactivity such as flour/grain dusts explode when mixed with air. The high mobility of the aerosol dusts made it possible to design a flow reactor which has no moving parts except the carrier gases and the reactants themselves. It was reasoned that since reactions between fluorine and hydrocarbons have very low activation energies, controlled reactions ought to result at low temperatures, which could be finely controlled by fluorine-concentration/temperature programing. This reasoning proved correct; good fortune and providence provided us with many beneficial effects we had not anticipated but which on discovery we took credit for.

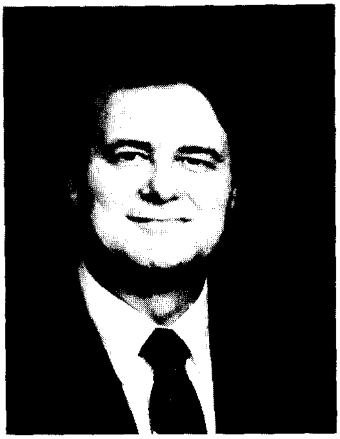
References

1 J. L. Adcock, K. Horita and E. B. Renk, *J. Am. Chem. Soc.*, *103* (1981) 6937.
2 W. Espenscheid, E. Matijevic and M. Kerker, *J. Phys. Chem.*, *68* (1964) 2831.

3 J. L. Adcock, K. Horita and E. B. Renk, 'Low Temperature Fluorination of Aerosol and Condensed Phase Sol Suspensions of Hydrocarbons Utilizing Elemental Fluorine', *Office of Naval Research, Contract Technical Report No. 3,* 1980.
4 J. L. Adcock and E. B. Renk, *U.S. Pat. 4 330 475* (1982).
5 J. L. Adcock and M. L. Robin, *J. Org. Chem., 49* (1984) 1442.
6 J. L. Adcock and W. D. Evans, *J. Org. Chem., 49* (1984) 2719.
7 J. L. Adcock, W. D. Evans and L. Heller-Grossman, *J. Org. Chem., 48* (1983) 4953.
8 J. L. Adcock and M. L. Robin, *J. Org. Chem., 49* (1984) 191.
9 J. L. Adcock and M. L. Robin, *J. Org. Chem., 48* (1983) 2437.
10 J. L. Adcock and M. L. Robin, *J. Org. Chem.,* submitted for publication.
11 J. L. Adcock and M. L. Cherry, *J. Fluorine Chem.,* in the press.

BIOGRAPHIC NOTE

James L. Adcock was born on June 26, 1943, in Crane, Texas. After studies at the University of Texas at Austin, where he received B.Sc. (1966) and Ph.D. (1971, under Joseph J. Lagowski) degrees, he was introduced to fluorine chemistry in the laboratory of Richard J. Lagow at Massachusetts Institute of Technology (1971 - 4). In 1974 he joined the faculty of the University of Tennessee at Knoxville, where his research interests include synthetic fluorine chemistry and aerosol direct fluorination of organic compounds.



J. L. Adcock

Appendix 11.11

The role of fluorocarbon gases in the microelectronics industry

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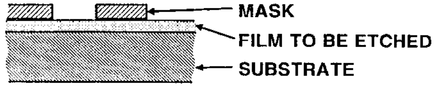
Fluorocarbons and their derivatives have played a major role in the development of many of our modern technologies, making possible, for example, the widespread use of safe and economical refrigeration and air-conditioning systems, the development of corrosion- and wear-resistant polymers and plastics, and the use of high-performance lubricants for critical aerospace applications. Today the microelectronics industry, with its continuing advances to process more information on a given integrated circuit, is dependent on fluorocarbon gases in the production of its most advanced microchips. The hand-held programmable calculator, digital watches and sophisticated computers we commonly use are made possible by these tiny chips which are capable of processing millions of pieces of information.

Integrated circuits (ICs) are composed of patterned layers of insulating, semiconducting and conducting thin films precisely defined by chemical etching processes to produce the desired electrical performance characteristics. Since the mid-1970s, integrated circuits have progressed from the 4K (4000 information bits) chips to the 256K (256 000 information bits). As the level of integration has increased, integrated circuit technology has reduced the dimensions of various circuit patterns with line-width approaching 1 μm, and in many cases equivalent to or less than the thin films.

For the earlier generation of microchips, with its line-widths of 10 μm or larger, 'wet' etching processes with liquid etchants such as hydrofluoric, phosphoric or nitric acid were used. However, these materials etch isotropically, *i.e.* equally in the vertical and lateral direction [Fig. 11.1(B)].

Since the layers that make up a complex IC have not decreased in thickness as fast as lateral dimensions, advances in etching technology were needed to proceed to finer line sizes. During the past decade, this problem has been solved by the development of 'dry' etching processes using a gaseous compound in the presence of an RF (radio frequency) glow discharge plasma to generate reactive species, which react with the substrate and form volatile etch products. For silicon integrated circuits, fluorine-containing compounds have become the dominant plasma etchant gases.

A plasma is a partially ionized gas formed by supplying RF energy to an etchant gas at reduced pressure (0.1 - 1 Torr). The plasma produced in such a 'glow discharge' is characterized by electron temperatures which are greater than the gas temperature by factors of 10 to 100. This means that chemical reactions which normally require elevated temperature to



(A) PATTERNED DEVICE BEFORE ETCHING

(B) ISOTROPIC PROFILE

(C) ANISOTROPIC PROFILE

Fig. 11.1. Etching profiles for integrated circuits.

proceed at a significant rate, can be promoted by the use of a glow discharge at room temperature. By control of electrical bias and other operating parameters, the etching process can be made directional or anisotropic [Fig. 11.1(C)].

The most common of the gaseous fluorine-containing compounds used to etch silicon type materials is carbon tetrafluoride (CF_4). In a glow discharge, a variety of species including electrons, positive ions, negative ions, fluorine atoms, CF_3 radicals and neutral CF_4 molecules will be present. The predominant etching species is the fluorine atom produced according to the equation

$$CF_4 + e^- \longrightarrow F\cdot + CF_3\cdot + e^-$$

In this case, the fluorine atom reacts with the silicon substrate to produce the volatile byproduct SiF_4.

Carbon tetrafluoride was first produced by Moissan by the direct fluorination of carbon following his discovery of fluorine in 1886. However, he produced a mixture of fluorocarbons and was not able to isolate pure CF_4. It was not until 1930 that the French chemists Lebeau and Damiens were able to isolate carbon tetrafluoride from the product formed by the reaction of elemental fluorine with wood charcoal. Ruff repeated this work in 1930 and fully characterized carbon tetrafluoride. Later, numerous investigators studied the preparation of carbon tetrafluoride. The methods of preparation which emerged can be categorized in four areas: (1) direct fluorination of carbon; (2) halogen exchange using hydrogen fluoride; (3) electrochemical fluorination using hydrocarbons; and (4) miscellaneous techniques generally using metal fluorides. On a commercial scale, halogen exchange became the most accepted process for the production of carbon tetrafluoride, using carbon tetrachloride and hydrogen fluoride as starting materials.

The development of plasma-etching technology using carbon tetrafluoride in the microelectronics industry placed new challenges on the fluorocarbon industry. Carbon tetrafluoride was produced as a minor byproduct in the production of the more common halocarbons — trichlorofluoromethane (CCl_3F), dichlorodifluoromethane (CCl_2F_2) and chlorotrifluoromethane ($CClF_3$). However, purity was not critical and the carbon tetrafluoride was available as a commercial grade of 98% purity, the contaminants being chlorofluorocarbons. With the critical requirements of the electronics industry, demands for higher purity products from both the chemical and particulate standpoint were required. This challenge has been met, and today high purity CF_4 (99.99+%) is commercially available.

This demand for high-purity carbon tetrafluoride has led to the development of new commercial processes. To eliminate totally any chlorine contamination, a process based on the reaction of carbon with fluorine has been commercialized, almost a century after Moissan performed his initial experiments. Many of the problems which prevented the scale-up of direct fluorination, such as reaction control polymerized products, corrosion and the handling of fluorine at elevated temperatures have been addressed and

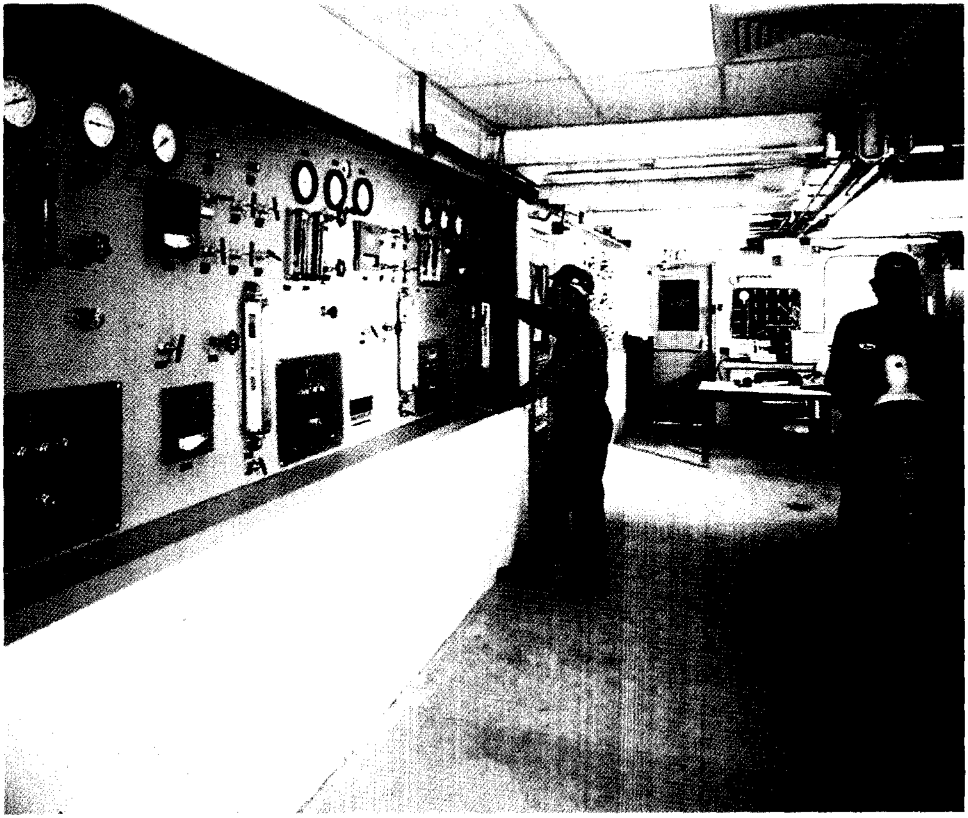


Fig. 11.2. Control room of a direct fluorination plant used to produce carbon tetrafluoride (CF_4) for the electronics industry. (Photograph reproduced by courtesy of Air Products and Chemicals, Inc.)

solved (Fig. 11.2). This process specifically directed to making carbon tetrafluoride for the electronics industry uses high-purity raw materials to give the fluorocarbon directly without any byproducts. Therefore, the processing required to purify the carbon tetrafluoride is greatly simplified; removal of the chlorofluorocarbon and hydrogen chloride byproducts is required in the halogen-exchange process.

Although carbon tetrafluoride continues to be the workhorse of the plasma-etching process in the electronic industry, a number of other fluorocarbon derivatives are used to etch a variety of silicon substrate films, such as polysilicon, single-crystal silicon, silicon dioxide, silicon nitride and tungsten silicides. In many cases, additives are used in conjunction with the base fluorine-containing gas to tailor the etch profile. Other organic fluorine compounds which find use in plasma etching include hexafluoroethane (C_2F_6), octafluoropropane (C_3F_8) and trifluoromethane (CHF_3); inorganic fluorine compounds such as nitrogen trifluoride (NF_3), sulfur hexafluoride (SF_6) and silicon tetrafluoride (SiF_4) are used too.

The microelectronics industry has presented a new opportunity and challenge for speciality fluorocarbons with its development of dry-etching processes. Although the volume of gases used in these applications is small, representing less than 1% of the total volume of the common halocarbons, they represent a unique new opportunity in the organofluorine business area.

BIOGRAPHIC NOTE

Andrew J. Woytek is the Director of Research and Technology (Speciality/Electronic Gases) in the Industrial Gas Division of Air Products and Chemicals, Inc.

A. J. Woytek

Appendix 11.12

Graphite fluoride

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Graphite fluoride is a gray-white solid prepared by the direct fluorination of a carbon material such as natural graphite or petroleum coke. The color varies mainly depending on the fluorination temperature. At present two crystal structures, $(CF)_n$, poly(carbon monofluoride) and $(C_2F)_n$, poly(dicarbon monofluoride) are known; $(C_2F)_n$ is obtained only by low-temperature fluorination of a high-quality graphite. $(CF)_n$ corresponds to the first stage intercalation compound of graphite, and $(C_2F)_n$ to the second stage. Both have a covalent bond between carbon and fluorine, therefore they are electric insulators, having no aromatic nature. Graphite fluoride is now being produced by several companies in Japan: Daikin Kogyo Co., output 50 tonne per year; Nippon Carbon Co., output 1 tonne per year; Central Glass Co., output 6 tonne per year.

Graphite fluoride is stable in a normal environment. The most important property is that it has a high electrochemical activity under cathodic polarization. This was discovered in 1970, and led to the development of

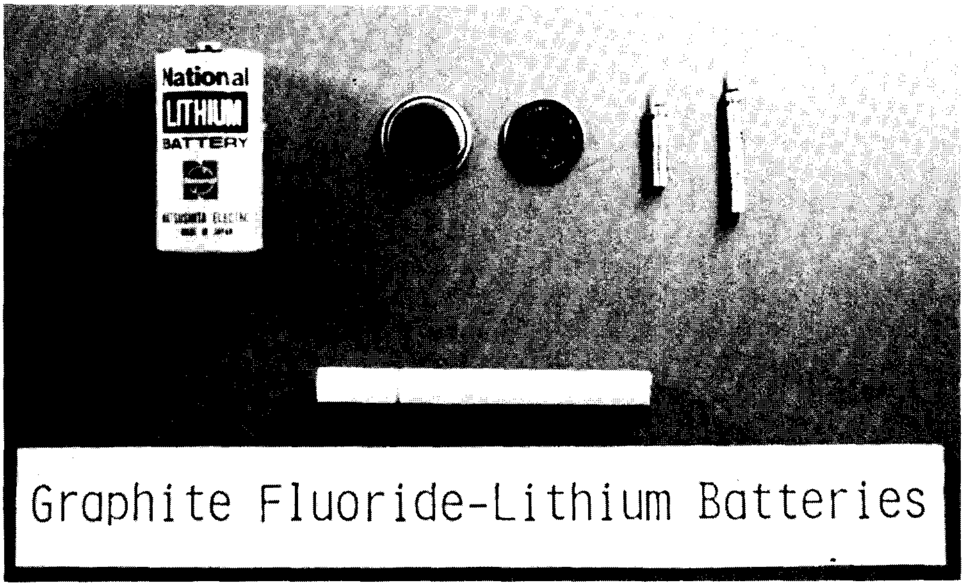

Fig. 12.1. Types of graphite fluoride/lithium batteries available commercially.

an Li/$(CF)_n$ primary battery using an organic electrolyte. In Japan, Li/$(CF)_n$ batteries are now in production on the industrial scale by the Matsushita Electric Co. They have many excellent characteristics, such as high voltage and energy density, flat discharge potential, discharge capability over a wide range of temperature, long shelf-life and consistent performance for long periods, and high safety. Three types of batteries are available, as shown in Fig. 12.1. Cylindrical batteries were the first to be commercialized and find use in wireless transmitters, analytical instruments, etc. The pin and coin types are employed as power sources for illuminated fishing floats, electronic watches, and so on.

Other characteristics of graphite fluoride are a lower surface energy than poly(tetrafluoroethylene) (PTFE) and excellent lubricity. These properties are utilized in adhesion-preventing agents and lubricants. The former are produced as aerosols containing finely-powdered graphite fluoride which allow the preparation of a thin film by spraying (Monolon Co.). Examples of the latter are grease and lubricant oil containing graphite fluoride produced by the Monolon Company, high-class gland packings made by impregnating graphite fiber textile with PTFE and graphite fluoride (available from Nippon Carbon Ltd.), and a composite nickel plating containing graphite fluoride developed by Uemura Kogyo Ltd.

BIOGRAPHIC NOTE

Nobuatsu Watanabe is a professor in the Department of Industrial Chemistry in the Faculty of Engineering at Kyoto University, a post he has held since 1966. He is a graduate of the same university (Bachelor, 1946; Doctor of Engineering, 1957), and has received prizes (Tanahashi Prize — Electrochemical Society of Japan, 1967; Japanese Chemical Society Prize, 1981) for his studies in fluorine chemistry, with particular reference to carbon–fluorine intercalates.

Appendix 11.13

Production and applications of Flutec® fluorocarbons

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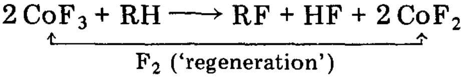
The commercial-scale production of Flutec® fluorocarbons — saturated compounds containing only carbon and fluorine atoms — by I.S.C.' Chemicals Limited at its Avonmouth works is the result of more than 30 years spent on the technical development of the cobalt fluoride fluorination process.

Production

The need in America in the early 1940s for highly stable fluids for use in plant handling uranium hexafluoride led Fowler to devise a process whereby vaporised hydrocarbons were fluorinated by cobalt trifluoride to give perfluorocarbon liquids (see Chapter 5). Professors Stacey and Tatlow and their co-workers at Birmingham University developed the process further [1], and Birmingham-type fluorination reactors were installed at Avonmouth in the 1950s (Fig. 13.1). These were horizontal tubular copper reactors, a few inches in diameter, with paddles ranged along a central rotating nickel shaft to improve contact between the cobalt trifluoride and the hydrocarbon vapour. The essential reaction is as follows:



$$2\,\mathrm{CoF_3} + \mathrm{RH} \longrightarrow \mathrm{RF} + \mathrm{HF} + 2\,\mathrm{CoF_2}$$

F_2 ('regeneration')

It was not practical to effect complete depletion of the cobalt trifluoride to the difluoride, and experience indicated the optimum time to discontinue the hydrocarbon feed and flush out the residual hydrocarbon and underfluorinated product before passing fluorine gas in to regenerate the cobalt trifluoride. Given the extremely vigorous nature of the reaction, and the corrosive and abrasive properties of fluorine and cobalt fluoride, a run that yielded a few kilogrammes of crude product mixture during several hours was regarded as entirely satisfactory.

Since those early days, continual attention to the chemical engineering aspects of the process have produced very significant improvements in the continuity of operation of both fluorine cells and fluorination reactors, and in the recovery and work-up of crude fluorocarbon products. Probably the most substantial single improvement was the development of a mechanically-fluidised bed-fluorination reactor and the process control technology that allowed the *simultaneous* introduction of hydrocarbon and fluorine into the cobalt fluoride bed. This was a major step forward in that it turned a batch operation into a continuous process and also afforded

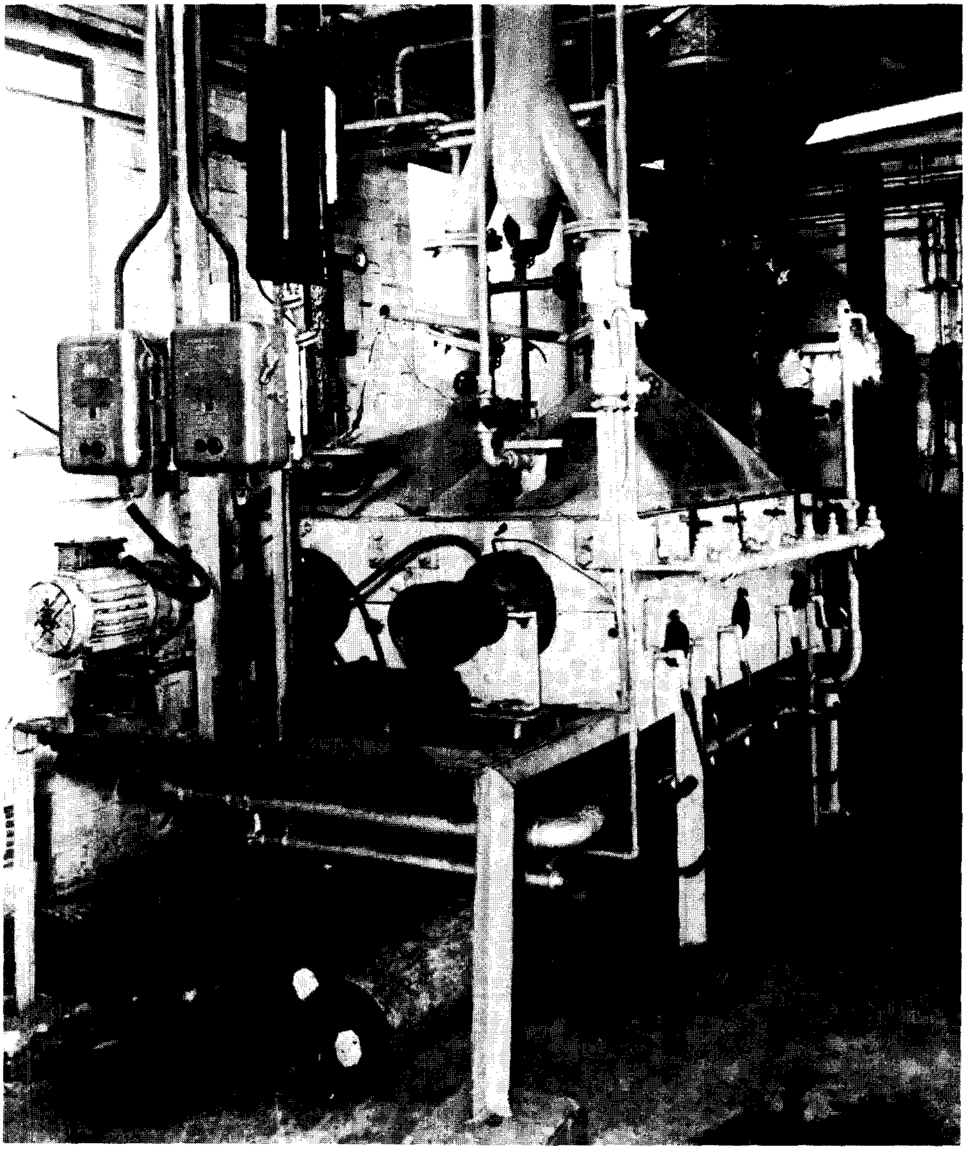


Fig. 13.1. A pair of CoF_3 reactors used by the author and R. E. Banks in A. K. Barbour's group at Avonmouth during the period 1956 - 58.

much finer temperature control throughout the reaction zone. Fluorination runs are now campaigns lasting many days and yielding tonnage quantities of crude fluorocarbon products. A number of such reactors of varying size, with a fluorine-generation facility (Fig. 13.2) that permits the simultaneous running of several reactors, gives I.S.C. Chemicals a flexible, truly commercial operation that underlines its worldwide reputation for the production of inert fluorocarbon liquids.

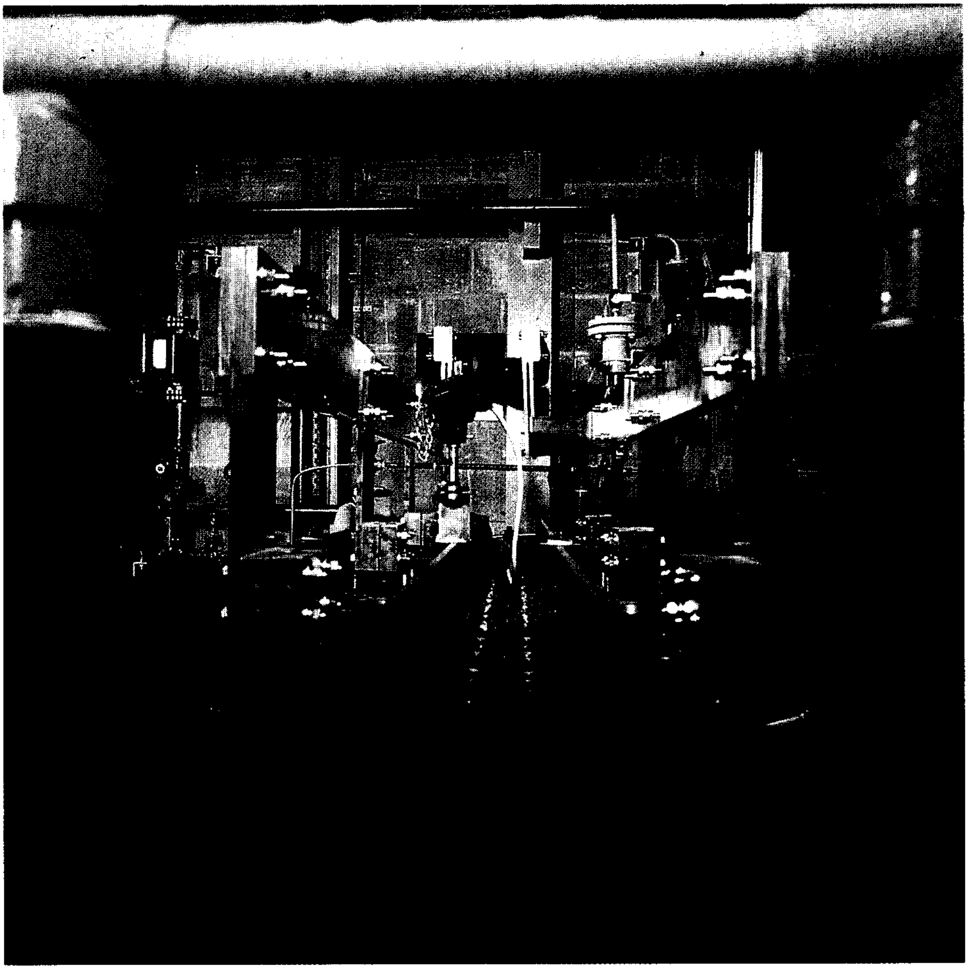


Fig. 13.2. Fluorine generation facility at Avonmouth.

The chemical and physical processes involved in the treatment of the crude fluorocarbon product essentially consist of steam distillation, extractive distillation, chemical treatment, drying and filtration. In order to achieve the unique stability properties expected of saturated fluorocarbons, it is essential to eliminate all traces of hydrocarbons and hydrofluorocarbons; the various stages of the purification process are designed to achieve this objective. A variety of analytical techniques are employed to ensure final product quality, gas chromatography being the major process control tool.

Properties

The physical and electrical properties of the current range of Flutec® fluids are listed in Tables 13.1 and 13.2, respectively.

TABLE 13.1

Physical properties of Flutec® liquids[a]

Property	PP50	PP1	PP2	PP3	PP5	PP9	PP11
Molecular weight	288	338	350	400	462	512	624
Density/kg l^{-1}	1.60	1.68	1.79	1.83	1.92	1.97	2.03
Boiling point/°C at 1 atm	29	57	76	102	142	160	215
Freezing point/°C	−120	−90	−30	−70	[b]	−70	−20
Viscosity (kinematic)/$mm^2\ s^{-1}$	0.29	0.39	0.873	1.06	2.66	3.25	14.0
Viscosity (dynamic)/mPa s	0.465	0.656	0.561	1.919	5.10	6.41	28.4
Surface tension/mN m^{-1}	9.4	11.1	15.4	16.6	17.6	18.5	19
Vapour pressure/mbar	862	294	141	48	8.8	2.9	2.0
Heat of vaporisation at boiling point/kJ kg^{-1}	90.8	85.5	85.9	82.9	78.7	75.5	68
Specific heat/kJ kg^{-1} °C^{-1}	1.05	1.09	0.963	0.963	1.05	1.09	1.07[c]
Critical temperature/°C	148.7	177.9	212.8	241.5	292.0	313.4	377[c]
Critical pressure/bar	20.48	18.34	20.19	18.81	17.53	16.60	14.6[c]
Critical volume/l kg^{-1}	1.626	1.582	1.522	1.520	1.521	1.500	1.58[c]
Thermal conductivity/mW m^{-1} °C^{-1}	64.0	65.3	59.9	60.4	57.0	57.5	52.6
Coefficient of expansion/°C^{-1}							
at 0 °C	0.00189	0.00159	0.00138	0.00123	0.00104	0.00097	0.00075
at b.p.	0.00213	0.00205	0.00190	0.00178	0.00170	0.00167	—
Refractive index (n_D^{20})	1.2383	1.2509	1.2781	1.2895	1.3130	1.3195	1.3348

[a] Temperature-dependent properties were determined at 25 °C.

[b] −11.2 °C to 18.0 °C, depending on the *cis/trans* ratio.

[c] Estimated values.

TABLE 13.2

Electrical properties of Flutec® fluids

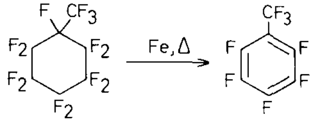
Property	PP50	PP1	PP2	PP3	PP5	PP9	PP11
Dielectric strength/ kV mm^{-1} at 50 Hz[a]	17	17	23	22	20	20	13
Resistivity/Ω m	10^{15}	10^{15}	10^{15}	10^{15}	10^{15}	10^{15}	10^{15}
Permittivity at 100 kHz	(1.7)[b]	1.70	1.82	1.93	1.95	1.99	(2.0)[b]
Loss tangent ($\times 10^4$) at 100 kHz	<1	<1	<1	<1	<1	<1	<1

[a] British Standard Specification 148/72.

[b] Estimated value.

Chemical and thermal stability

Flutec® fluorocarbons show exceptional thermal stability, with maximum working temperatures generally in excess of 400 °C. Extreme resistance to chemical attack is demonstrated in that they are unaffected by boiling concentrated acids and alkalis, and also by oxidising and reducing agents under normal conditions. Virtually the only chemical reactions of Flutec® fluids are with molten alkali metals, with glass or silica at temperatures above 500 °C and with iron or nickel at *ca.* 500 °C when defluorination occurs to yield aromatic fluorocarbons. In fact, this has been used as a route to octafluorotoluene, but is hardly a commercially viable process:



perfluoro(methylcyclohexane) octafluorotoluene

Flutec PP2

Electrical stability

High dielectric strengths, high resistivities, low permittivities and very low dielectric losses combine to make Flutecs excellent insulants. They are not affected by electrical or magnetic fields or by corona discharge. Ready absorption of fast electrons (electron capture) gives exceptional arc-extinction properties, albeit sometimes accompanied by slight breakdown of the fluorocarbon to produce CF, CF_2 and CF_3 fragments which then recombine to give gaseous small molecules.

Heat-transfer properties

Flutecs have high fluid densities, low viscosities, high coefficients of expansion and very low latent heats of vaporisation, properties which combine to make them excellent heat-transfer media.

Safety

On the basis of extensive toxicological studies, Flutec® fluorocarbons are classified as 'practically non-toxic', the lowest rating on the toxicity scale. In addition, they are totally non-flammable and non-explosive.

Areas of application

The varied applications for Flutec® liquids have been described in detail in a recent publication [2]. The following brief treatment is intended to indicate the variety of such applications and the properties that have led to the selection of specific liquids for particular jobs. In tonnage terms, electrical and electronic applications currently comprise the largest single area of application, which involves (a) assembly processes, (b) device testing and (c) operational coolants.

Assembly processes

Condensation soldering, also referred to as 'vapour-phase soldering' or 'vapour-phase solder reflow' is a technique for producing high reliability soldered joints in printed circuits quickly and easily. When large numbers of soldered joints have to be made in close proximity to each other, as is necessary with the increasing miniaturisation of electronics circuitry, hand assembly becomes impractical.

A variety of automated techniques have been devised, but condensation soldering has emerged as one of the most attractive. Pre-soldered components are positioned on the circuit board, which is then passed through the vapour of a boiling fluorocarbon liquid. Choice of liquid is primarily determined by the melting point of the solder, and Flutec PP11, b.p. 215 °C, is most commonly used since the usual tin/lead solders melt about 20 °C below this temperature. Fluorocarbon vapour condenses on the cold circuitry, raising the temperature rapidly and evenly until the solder melts and flows. Thermal stress is minimised since no part of the assembly can become overheated; complicated and three-dimensional assemblies are readily treated, and the exclusion of oxygen prevents oxide formation on the solder.

Since there are occasions when higher-melting solders are needed, one aspect of the Flutec development programme is directed towards finding fluids with higher boiling points while retaining all the safety and efficacy features of Flutec PP11. It is probably no exaggeration to say that the development of the condensation soldering process [3] was critically dependent on the availability of inert fluorocarbon liquids having the right combination of properties: inertness towards constructional materials, high thermal stability, non-flammability, extremely low toxicity and rapid 'clear' evaporation rates (no residue).

Testing procedures

In order to ensure reliability and guarantee the performance of electronic devices under arduous service conditions, a variety of test procedures have been devised, which include (i) leak testing, (ii) burn-in testing, (iii) steady-state life testing, (iv) thermal shock testing and (v) hot-spot location. Leak testing is applied to devices in which the circuitry is encapsulated in a package of metal, ceramic or plastic. For maximum reliability, such packages should be hermetically sealed to prevent the entry of traces of moisture or particulate matter. Pin holes in the encapsulating medium may be detected by immersing the device in a fluid at an elevated temperature, against an illuminated black background. The presence of a pin hole is indicated by a fine stream of air bubbles issuing from it. Flutec PP9, b.p. 160 °C, is commonly used, being one of the liquids approved for testing to U.S. Military Standard 883a.

The advantages of fluorocarbon liquids for this type of test are the absence of flammability, toxicity and corrosion hazards, plus the advantage of not having to clean the device after testing because the fluorocarbon drains off rapidly and completely. In addition, should traces of fluorocarbon enter the device through an undetected leak, the chemical inertness and electrical properties are such that subsequent electrical malfunction is very unlikely. There is, in fact, a variant of the test in which a low boiling fluorocarbon such as Flutec PP1 (b.p. 57 °C) is forced into fine pin holes by means of an evacuation/immersion technique. When such pre-treated devices are subsequently put into the usual hot fluorocarbon bath (125 °C), volatilisation of the low-boiling fluorocarbon generates far more vapour than with just air alone, and the sensitivity of the test is increased by as much as 1000-fold.

All the other forms of testing are designed to accelerate thermal or electrical stress. Devices can be operated at extremes of temperature, typically −60 °C to 150 °C, with rapid transition from one temperature to the other by moving the device from one liquid bath to another. They can also be run at constant elevated temperatures for periods of up to 1000 h, which enhances age-related deterioration of components. In all such tests an inert liquid environment provides steady test conditions and excludes extraneous factors. The choice of fluid or fluids is dictated by the desired operating conditions.

Operational coolants

Inert fluorocarbon liquids were first proposed as dielectric coolants in transformers and switchgear some 20 years ago. They are in many ways ideal for such purposes but the relatively high cost prevented significant commercialisation. The increasing miniaturisation of electronics assemblies, sometimes coupled with arduous service conditions, has introduced a different scale of potential overheating problems. These are best solved by total immersion of the equipment in a liquid coolant, but the need for an inert electrical environment, the safety requirement and the wide variety of materials encountered in such equipment makes selection of a suitable fluid very difficult. Only an inert fluorocarbon liquid satisfies all requirements and Flutec fluids find application in a variety of military and aerospace equipment. The significantly better cooling performance of fluorocarbons, whether in convective cooling or in the pool-boiling mode, has been used with advantage in equipment such as klystron valves, travelling wave tubes, transformers, thyristors and resistor stacks. Most of the Flutec range have been employed at one time or another for cooling purposes, with Flutec PP3 (b.p. 102 °C) being possibly the most widely used.

Air mass movement; explosives detection

Though totally different, these applications utilise the electron-attachment properties of certain fluorocarbons, notably those having cyclic structures with substituent trifluoromethyl groups. By means of a gas chromatograph fitted with an electron capture detector [4] it is possible to detect compounds such as perfluoro(methylcyclohexane) (Flutec PP2) at levels as low as one part in 10^{15}. The major use of this technique at present is in tracing the movement of exhaust gas emissions from power station stacks. Environmental concern regarding possible effects on plant and aquatic life (acid rain) is resulting in a significant programme of such investigations, both in Europe and North America.

Regarding detection of explosives, the growing problem of international terrorism has led to a search for better methods of detecting explosives concealed in, for example, aircraft baggage. Studies in the U.S.A. [5] showed that microencapsulated fluorocarbons incorporated in explosives can readily be detected by an EC/GC technique. Perfluoro(dimethylcyclohexane) (Flutec® PP3) was selected as the best candidate overall on grounds of commercial availability, safety, environmental acceptability and microencapsulation/permeation performance. Practical studies on airport baggage handling facilities have demonstrated the feasibility of the technique [6] on a continuous basis, but legal and operational restraints have held up implementation to date.

Medical applications

It is now 20 years since medical researchers demonstrated that emulsions of fluorocarbons can be used to transport oxygen to organs of the body, a development which is often referred to as 'artificial blood'. The key factor is the ability of fluorocarbons to dissolve substantial volumes of gases, oxygen and carbon dioxide being the relevant gases in this context, and the miscibility of fluorocarbon emulsions with whole blood. Several extensive reviews [7 - 10] exist of the development of this concept from the first isolated organ experiments to the present time, during which period more than 1000 patients have received fluorocarbon emulsions during clinical trials. Registration procedures are in progress in Japan and the U.S.A.

Though the present emulsions are capable of improvement, in that they have to be stored in the frozen state and thawed out shortly before use, the fluorocarbon of choice to date is perfluorodecalin (Flutec® PP5). This could, of course, change if one or other of the several active programmes on emulsion improvement should indicate that a different compound is preferable. One additional drawback with present emulsions is that perfluorotripropylamine, used in conjunction with perfluorodecalin to improve emulsion properties, appears to be retained in the body for extended periods, whereas perfluorodecalin is completely lost from the body in a matter of seven to ten days.

In addition to straightforward replacement of blood loss without the need for blood-type matching, a number of other possible medical uses have been proposed, and some of these are showing encouraging initial results. Thus, the fine particle size of fluorocarbon emulsions, about one-tenth the size of red blood cells, suggests the possibility of improving the blood supply through partially-constricted blood vessels and hence providing a technique for preventing or treating heart attacks or strokes. Encouraging initial results have been reported for cancer therapy, where prior administration of a fluorocarbon emulsion appears to double the effectiveness of radiation treatment, presumably by increasing the oxygen supply to tumour tissue. Other possibilities include the prevention of anaerobic conditions developing under dressings in burn treatment, use in the treatment of eye disorders and applications in organ storage for transplant surgery and extracorporeal blood oxygenation, such as in the use of a heart/lung machine during heart surgery.

References

1 M. Stacey and J. C. Tatlow, *Adv. Fluorine Chem.*, *1* (1960) 166.
2 R. E. Banks (ed.), *Preparation, Properties and Industrial Applications of Organofluorine Compounds*, Ellis Horwood, Chichester, 1982, p. 55.
3 R. C. Pfahl and H. H. Ammann, *U.S. Pats. 3 866 307* (1975), *3 904 102* (1975) and *3 947 240* (1975) (to Western Electric).
4 P. G. Simmonds, A. J. Lovelock and J. E. Lovelock, *J. Chromatogr.*, *126* (1976) 3.
5 *Explosives Identification and Detection*, Aerospace Corporation, Washington, DC (on behalf of the U.S. Dept. of the Treasury); *Annu. Rep., No. ATR-80 (5860-01)-IND* (1980).
6 R. N. Dietz and R. W. Goodrich, 'The Continuously Operating Perfluorocarbon Sniffer (COPS) for the Detection of Clandestine Tagged Explosives', *Rep. BNL-28114* (1980) (Order No. PB81-155053) (*Chem. Abs.*, *95* (1981) 135 231h).
7 *Int. Symp. Artificial Blood, Bethesda, MD*, April 1974; *Fed. Proc., Fed. Am. Soc. Exp. Biol.*, *34* (1975) 1428.
8 R. Frey, H. Beisbarth and K. Stosseck (eds.), *Proc. 5th Int. Symp. Oxygen-carrying Colloidal Blood Substitutes, Mainz, March 1981*, Zuckschwerdt Verlag, Munich, 1982.
9 T. Mitsuno, H. Ohyanagi and R. Naito, *Ann. Surg.*, *195* (1982) 1.
10 M. Le Blanc and J. G. Riess, in R. E. Banks (ed.), *Preparation, Properties and Industrial Applications of Organofluorine Compounds*, Ellis Horwood, Chichester, 1982, p. 83.

BIOGRAPHIC NOTE

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Brian Joyner is the Business Development Manager at I.S.C. Chemicals Ltd. His involvement in the company's fluorochemical development programme over the past 30 years has included basic laboratory research, process development and investigation, quality control, customer technical support and applications technology. He is now concerned with the development of new business opportunities and associated product environmental and regulatory affairs.