Recent Advances in C−F Bond Activation

Juan Burdeniuc, Brigitte Jedlicka, and Robert H. Crabtree*

Yale Chemistry Dept.,
225 Prospect St., New Haven CT 06511, USA
Fax: (internat.) +1(203)432-6144
E-mail: crabtree@pantheon.yale.edu

Received August 16, 1996

Keywords: Fluorocarbons / C−F bond activation

The main reaction pathways which lead to the breaking of C−F bonds in perfluoroalkanes and -arenes are discussed. Emphasis is placed on recent developments and on the mechanistic patterns that emerge.

Fluoroorganic compounds continue to attract interest both for their unusual chemistry and for their many technological applications[1]. Such compounds can in principle be made from functionalization of the corresponding perfluoroalkanes and this goal has led to an increasing interest in the chemistry of C−F bonds in the last few years. This area shares certain aspects with the related but older problem of C−H bond activation[2] in hydrocarbons, but an important difference is that the enhanced value on going from the perfluorocarbon to the corresponding perfluorinated functional derivative is often much greater than is the case for hydrocarbons and so makes it practical to use more sophisticated reagents.

Fluorocarbons are highly resistant to oxidative degradation, a property that makes them indispensable for many applications but carries with it the disadvantage that the atmospheric lifetimes of these species can exceed 2000 years[3] (see Table 1).

Fluoroalkanes are global-warming gases[4] and chlorofluorocarbons (CFCs) have both global-warming and ozone-depletion potential. Some of the interest in C−F chemistry has been prompted by the need to convert CFCs into disposable solid products or to hydrogenated derivatives with lower ozone-depletion potential.

This review covers the title area with emphasis on developments since the last major review by Richmond et al.[5a]. A number of earlier related reviews are also available[5b−d].

Properties of Fluorocarbons

Aliphatics

Fluorine is unique in that it is the only element that can completely replace hydrogen wherever it occurs in hydrocarbons. Many physical properties of the resulting perfluorocarbons differ significantly from those of the corresponding hydrocarbons. In the case of boiling points, the

The picture shows the authors at their weekly lunch discussion. Juan Burdeniuc (left), a graduate student in Dr Crabtree's group, has discovered a number of new CF activation reactions, including a CFC disposal method using sodium oxalate. He previously worked with David Milstein. Brigitte Jedlicka, a postdoctoral fellow from Vienna in Dr Crabtree's group, has discovered some unusual CF activation chemistry over semiconductor materials. Formerly she worked on enantioselective catalysis with platinum metal complexes. Robert H. Crabtree, Professor of Chemistry at Yale, previously studied CH activation, halocarbon and H_2 complexes and is now working on fluorocarbon chemistry and outer sphere interactions in metal complexes.

MICROREVIEWS: This feature introduces Berichte's readers to the authors' research through a concise overview of the selected topic. Reference to important work from others in the field is included.

0009−2940/97/0202−0145 $ 15.00+.25/0

Table 1. The atomospheric lifetimes of some fluorocarbons and CFCs, after Warren et al.[a]

Compound	Atmospheric half life (years)
CF_4	$>5.0 \times 10^4$
C_2F_6	$>1.0 \times 10^4$
$c\text{-}C_4F_8$	3.2×10^3
C_4F_{10}	$>2.6 \times 10^3$
C_5F_{12}	4.1×10^3
C_6F_{14}	3.1×10^3
$(CF_3)_2\text{-}c\text{-}C_4F_6$	2.9×10^3
CF_3Cl	640
CF_3CF_2Cl	1.7×10^3
CF_2ClCF_2Cl	300
SF_6	3.2×10^3

[a] The major pathways considered were photolysis (Lyman α band: 121.6 nm) and reaction with O (^1D).

normal expectation would be that the fluorocarbon, having the higher MW, should also gave the higher b.p. This is not the case, however, because the increase in MW is offset by a decrease in the attractive intermolecular forces, the fluorocarbon having a much lower polarizability than the corresponding hydrocarbon, and induced dipole forces are less strong[6]. *Partial* substitution by fluorine leads to a increase in b.p. because of the high polarity of partial substitution products such as CHF_3. As the fluorine content progressively increases in the fluoromethanes, the energy of the C−F bonds increases and the bond lengths shorten as shown in Table 2[7]. Pauling proposed a double bond−no bond resonance structure to explain the bond shortening but in the alternative m.o. picture, the C−F σ^* orbital acts as acceptor for the lone pairs of the other F groups[8]. An alternative rationalization that has gained popularity in recent years is the Coulombic contribution to the C−F bond energy which also increases on increasing F substitution; extensive calculations have been offered in the literature[9]. Complete substitution of H by F also affects other physical properties: densities and viscosities increase, while refractive indexes and surfaces tensions decrease[10].

Table 2. Bond strengths of some fluorocarbons

Compound	Bond dissoc. energy (kcal/mol)	d(C−F) (Å)
CH_3F	109.0	1.385
CH_2F_2	122.0	1.358
CHF_3	128.0	1.332
CF_4	129.7	1.317

Perfluoroalkanes and perfluoroalkyl derivatives are exceptionally good solvents for O_2 and they have been used as blood substitutes. In certain circumstances[11] the entire blood of a mammal can be replaced by a fluorocarbon emulsion without ill effect; the normal blood regenerates over several days and the perfluoro derivative is lost by evaporation[12]. The blood substitute produced by 3M Corp. contains 12% of FC-47®, composed mainly of perfluoro-tri-*n*-butylamine, and Pluronic F-68®, a polyethylene oxide/polypropylene oxide block polymer as surfactant. The high solubility of nonpolar solutes is associated with the very low intermolecular forces in fluorocarbons, as are the nonstick properties of polymers such as teflon®[13].

The solubility of perfluorocarbons in common organic solvents is often much lower than that of the corresponding hydrocarbons and very often two-phase systems are formed which can homogenize with increasing temperature[14]. This property has been used to good effect in homogeneous catalysis by Horvath. In one application a fluorocarbon-soluble catalyst is dissolved in perfluoromethylcyclohexane and a hydrocarbon substrate for a catalytic reaction is dissolved in toluene. On heating to reaction temperature, the two phases become miscible, the catalytic reaction occurs, and on cooling the reaction mixture spontaneously separates into hydrocarbon and fluorocarbon phases, leading to facile separation of the catalyst from the substrate[15].

Perfluoroalkanes and perfluoroalkyl species are extremely inert. One important factor in the stability of these compounds is the high C−F bond energy, which is typically 120−125 kcal/mol for sp^3 C−F bonds[16]. Another factor is the apparent inability of the CF_3X fragment to undergo S_N2 nucleophilic attack at carbon. This may be connected with the steric size of the F groups disfavoring attainment of the required $Nu{-}CF_3{-}X$ transition state, and the shielding of the carbon by the nonbonding electron pairs on fluorine[17].

In the case of $R_f{-}I$, (where R_f is a perfluoroalkyl group), the polarity of the C−I bond is reversed relative to the situation in R−I, leading to nucleophilic attack taking place at the I rather than at carbon. $R_f{-}I$ is therefore not a source of R_f^+[18]. Other observations suggest that $R_f{-}I$ can also undergo attack via electron transfer (ET) processes, and $R_f{-}I$ is known to form charge-transfer complexes which could be precursors to the ET reaction[19]. Perfluorocarbons have electron affinities that are high enough for electron transfer to take place from good reducing agents[20]. They are very poor Lewis bases, having even less tendency than alkanes to undergo protonation or bind to a transition metal. The other halocarbons are all better donors and can form isolable complexes; a review of halocarbon complexation to transition metals is available[21].

Arenes

Perfluoroarenes are more reactive than their saturated analogues and can both undergo nucleophilic attack and more readily accept an electron from a reductant[22]. Part of the driving force for conversion of fluoroalkenes and arenes to the corresponding saturated derivatives comes from the repulsion between the F lone pairs of F atoms directly bound to sp^2 carbons and the π electrons of the unsaturated fragment[23]. This accounts for the large exothermicity of C_2F_4 polymerization.

Conversely, perfluoroalkyl and -aryl groups form unusually strong bonds to π-donor metal fragments in complexes of the type $L_nM(CF_3)$ and $L_nM(C_6F_5)$. Partial M−C double bonding is often proposed as a result of electron donation from the M d_π orbitals into the C−F σ^* of an alkyl group or the π^* of an aryl group, but the presence of large Coulombic effects has been suggested as an alternative rationalization[24]. Complexes of the type $L_nM(\eta^6\text{-}C_6F_6)$ are rather rare, although this may be because of lack of synthetic efforts rather than any instability.

Strategies in C−F Activation

Electron Transfer Pathways: Reactions of C−F bonds often proceed by initial electron transfer from a reductant, followed by scission of the C−F bond to give a carbon radical and a fluoride ion. The process is assisted by the use of a polar medium and by provision of an electrophile to accept the newly formed fluoride ion.

$$R_fCF_2{-}F + e^- = R_fCF_2^{\bullet} + F^- \qquad (1)$$

Electrophilic Pathways: Powerful Lewis acids can remove F^- from perfluoroalkanes, but other electrophilic reagents are thought to react by a radical mechanism. A good example, involving Pr^+ (Pr = Praseodymium), is recognized in the gas phase[48].

Homolytic Pathways: Even when the process is exothermic, F-atom abstraction from perfluorocarbons seems to be very slow. For example, in studies on perfluoromethylcyclohexane, no HF formation was observed on reaction with $Hg/H_2/h\nu$, a copious source of H atoms.

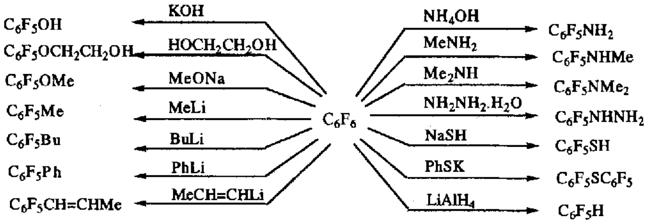
$$C{-}F + H^{\bullet} \xrightarrow{\text{very slow}} \underset{\text{not observed}}{C^{\bullet} + H{-}F} \qquad (2)$$

The H−F bond strength (136 kcal/mol) substantially exceeds the C−F bond strength (120 kcal/mol) in this case, indicating that the reaction has a substantial driving force. This means that HF abstraction from fluorocarbons has a very much higher barrier than the well-recognized H_2 abstraction from alkanes; this does not seem to have been adequately explained since polar effects would normally be expected to favor HF abstraction.

Oxidative Addition: This reaction, the insertion of a metal into a C−F bond, is often observed, especially with perfluoroarenes. However, it is not yet clear whether it is truly concerted or is initiated by electron transfer or electrophilic steps. The metal fragments capable of bringing about the reaction are all highly reducing, so an initial electron transfer cannot yet be excluded. Initial binding of the metal to the π-system of the arene is also a plausible initial step as is often the case for the hydrocarbon analogues[49].

Nucleophilic Pathways: Perfluoroarenes preferentially undergo nucleophilic attack in contrast to perhydroarenes which tend to undergo electrophilic attack. This is an example of the inversion of reactivity often seen between fluorocarbons and hydrocarbons. A large number of polyfluorinated arenes have been prepared by this route (Scheme 1)[50].

Scheme 1. Reactions of hexafluorobenzene with nucleophiles



Displacement of fluorine occurs by a two-step mechanism with the nucleophilic attack being rate determining[51]. Formation of charge-transfer (CT) complexes may be involved in the reaction pathway, but their formation is very rapid and not rate determining.

Activation of Aliphatic C−F Bonds

Perfluoroalkanes

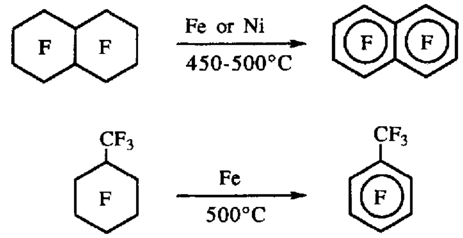
Reactions of perfluoroalkanes are still relatively rare. Several long-known examples require forcing conditions and tend to be unselective. Alkali metals react, but only at 400−500 °C, to give the alkali fluoride and carbon; this reaction has practical use in the determination of the fluorine content of analytical samples[52]. Na/NH_3 reacts at room temperature, although only very slowly[53a], and this is the method currently used commercially[53b] for the disposal of CFCs[53]. Above 600 °C, reaction occurs with silica according to eq. 3[54].

$$C_2F_6 + 1.5\,SiO_2 = CO + CO_2 + 1.5\,SiF_4 \qquad (3)$$

On reaction of higher fluorocarbons with F_2, cracking of the molecule takes place via C−C bond cleavage to give lower fluorocarbons[55]. A similar reaction occurs with H_2 at 700−900 °C or with Cl_2 or Br_2 at 900 °C, the products being hydrofluorocarbons such as CHF_3 and C_2F_5H[56] or chloro- or bromofluorocarbons[57a]. Teflon can also be cracked to C_2F_4 at 600 °C[57b]. Since unsaturated fluorocarbons are often much more reactive than their saturated counterparts, any practical method for the preparation of olefins or arenes requires an efficient method for product protection, for example by rapidly removing products from the reaction zone. This problem is similar to that found in the partial oxidation of alkanes, where overoxidation has to be avoided[58].

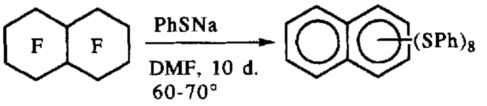
With Ni or, better, Fe at 400−600 °C, cyclic perfluorocarbons can be aromatized (Scheme 2), where the volatility of the arene allows it to be rapidly removed from the reaction zone. This reaction constitutes a general method for the preparation of aromatic products and is practiced on a commercial scale[59].

Scheme 2



Other reactions with perfluorocarbons, known at lower temperatures, give either full or partial defluorination, but more sophisticated reagents are needed. Sodium arenethiolates slowly react with cyclic perfluorocarbons that have a tertiary carbon center to give complete defluorination and aromatization (Scheme 3). Perfluorocarbons with tertiary C−F bonds are relatively more reactive towards electron transfer than those with primary or secondary bonds, due to their lower C–F σ^* energies[60]. As mentioned above, perfluorocarbons are used as artificial blood substitutes but the presence of thiols and other nucleophiles in biological fluids means that perfluorocarbons may not in fact be as completely inert in biological systems as has been assumed, given their potential for reaction with nucleophiles.

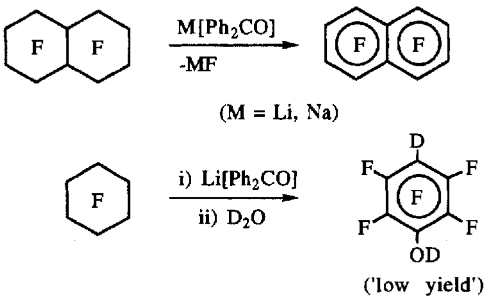
Scheme 3



Conversion of polytetrafluoroethylene (PTFE) into polyethylene (PE) has been reported using lithium in liquid ammonia[61]. When lithium is the limiting reagent, formation of elemental carbon is also observed. However, when lithium is in excess, conversion of PTFE into PE occurs in 90% yield.

Selective partial reduction of perfluorocarbons was obtained by using the sodium benzophenone radical anion in THF.

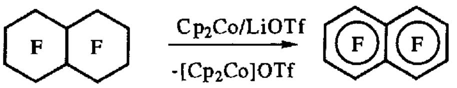
Scheme 4



Perfluoronaphthalene and perfluorophenanthrene are obtained by reaction of their saturated analogues with sodium benzophenone, with yields of 62% and 22% respectively after hydrolysis. Perfluorocarbons with no tertiary carbon, such as perfluorocyclohexane, also react to give 1,2,4,5-tetrafluorophenol in low yield (Scheme 4). Linear perfluorocarbons, such as n-C_8F_{18}, also react to give NaF and carbon, however[62].

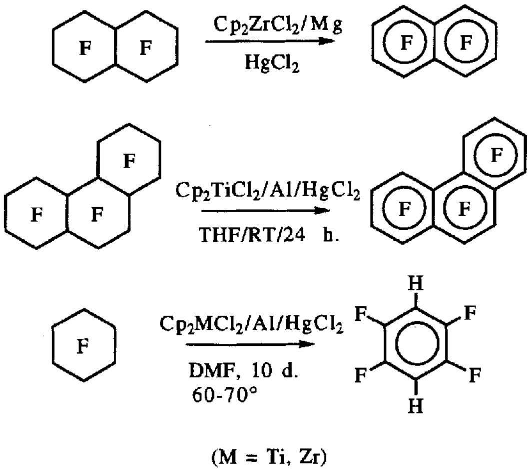
Richmond has shown that cobaltocene reacts stoichiometrically with perfluorodecalin in the presence of LiO_3SCF_3 to give perfluoronaphthalene (Scheme 5). When the reaction is carried out with an excess of perfluorodecalin in toluene, and in the absence of LiO_3SCF_3, a greenish precipitate of $[Cp_2Co]F$ is obtained which can be used as a source of nucleophilic fluoride ions[63]. The fate of the perfluoroalkane was not determined.

Scheme 5



Very recently, stoichiometric and catalytic C–F bond activation was achieved by using early transition metallocenes. The active species were generated from Cp_2ZrCl_2 and Mg/$HgCl_2$; Cp_2TiCl_2 and Al/$HgCl_2$ or Cp_2TiCl_2 and Mg/$HgCl_2$ are used as catalysts for the aromatization of cyclic perfluorocarbons at room temperature (Scheme 6). The low-valent zirconocene complex "$ZrCp_2$", generated either photochemically [via reductive elimination of biphenyl from $ZrCp_2(Ph)_2$] or from Cp_2ZrCl_2/2 BuLi, can effectively defluorinate perfluorodecalin to perfluoronaphthalene, and has therefore been considered as a possible intermediate in the catalytic cycle. The chemistry is not limited to substrates with tertiary centers since perfluorocyclohexane can also react to give 1,2,4,5-tetrafluorobenzene[64].

Scheme 6

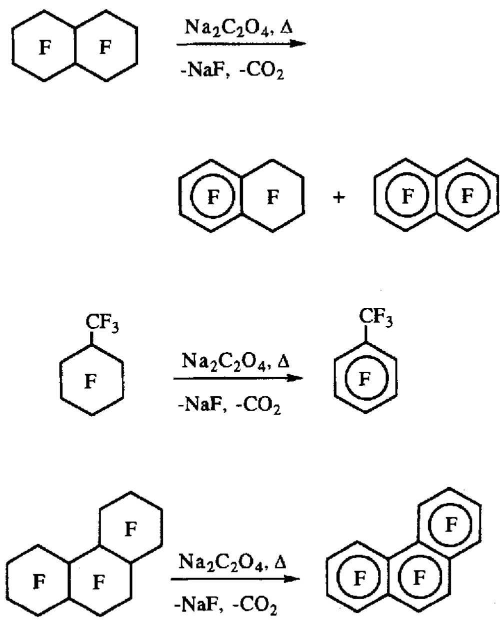


Low-temperature activation of C–F bonds in perfluoroalkylethers has been reported with an atomically clean iron surface under ultra-high-vacuum conditions. The defluorination process yields iron fluoride, and dissociation of the unsaturated product from the surface follows. No mechanistic explanation for this unusual reaction has been given, but the low temperature at which it occurs (155 K) suggests an ET pathway. Presumably, the driving force for this reaction is the formation of strong Fe–F bonds. Similarly, activation of CH_2F_2 occurs at 156 K on an Fe(110) surface, via selective abstraction of the fluorides, to form FeF_2 and $:CCl_2$[65].

Most defluorination processes involve the use of reducing agents, and mechanisms involving electron transfer have been proposed for most of them. Therefore, these reactions are strongly dependent on the electron affinities of reagents and products. Since the reported electron affinities of perfluoroarenes are smaller than those of perfluoroalkanes[20], isolation of perfluoroarenes is then in principle possible. Perfluoroalkyl carbanions are likely intermediates in the reaction process. They are sufficiently stable to be studied spectroscopically and isolated. Methods for their preparation have also been described[66].

A new thermal method for the aromatization of cyclic perfluorocarbons, from our group, uses an inexpensive and noncorrosive compound, sodium oxalate, as reducing agent (Scheme 7). By passing a stream of inert gas, such as N_2 or Ar, saturated with the perfluoroalkane through a packed bed of the heated salt, solid aromatic products can be collected in an air-cooled condenser. Under certain conditions perfluorotetralin can be the major product from perfluoronaphthalene. The reaction can also be used for the mineralization of CFCs by converting these environmentally hazardous materials into easily handed solids: carbon, sodium fluoride and sodium chloride[67]. The oxalate is thought to act as a 1e donor to the halocarbon: some C_2Cl_6 is formed from CCl_4, suggesting that $\bullet CCl_3$ is an intermediate. The crystal surface is considered to be a polar medium, analogous to a polar solvent in the condensed phase. Electrophilic assistance for the loss of a fluoride ion from the fluorocarbon is in principle available in the form of an anion vacancy on the crystal surface.

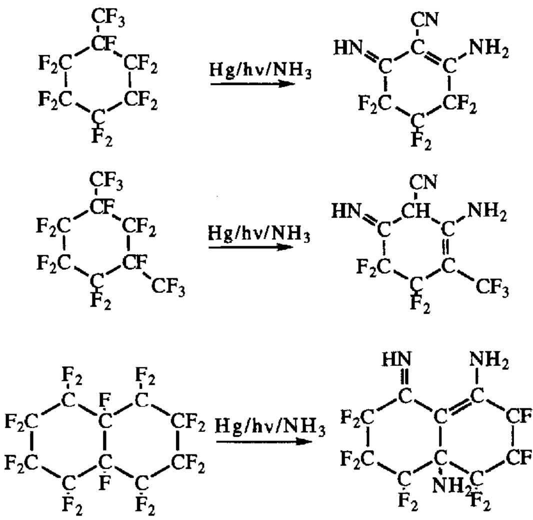
Scheme 7



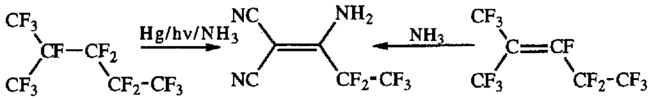
In a recent report we describe a partial reduction of perfluoroalkanes and PTFE by ammonia with mercury photosensitization (Scheme 8). In Hg photosensitization, which has previously been used for the activation of C−H bonds on a preparative scale, the $^3P_1$ mercury excited state can induce homolytic cleavage of C−H bonds to give carbon radicals which recombine or give other reactions with unusually high selectivity. This approach has been successful for the preparation of a number of hydrocarbon derivatives directly from the alkane[68].

Although perfluorocarbons are inert to attack by radicals under mild conditions, perfluorocarbons react with NH_3 under Hg photosensitization to give amine, imine and cyano-derivatives, depending on the structure of the alkane. The reaction seems to occur by electron transfer from an exciplex such as $[Hg^*(NH_3)_2]$ whose calculated IP is very low and comparable to that of Cs. However, other intermediates could not be eliminated. The final products in these reactions are believed to be formed from an intermediate alkene that rapidly reacts with ammonia by thermal pathways to give the final products (Scheme 9)[69].

Scheme 8

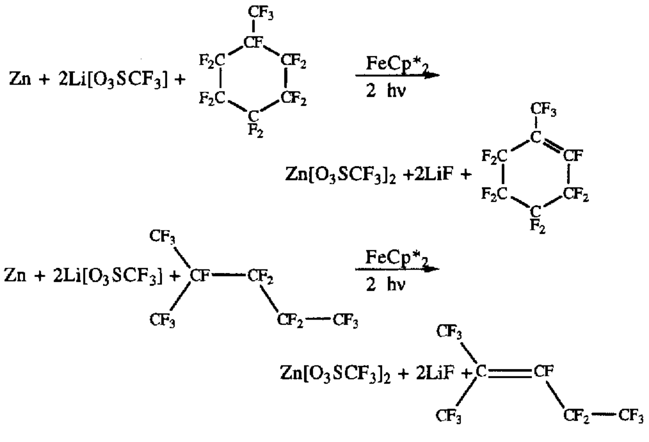


Scheme 9

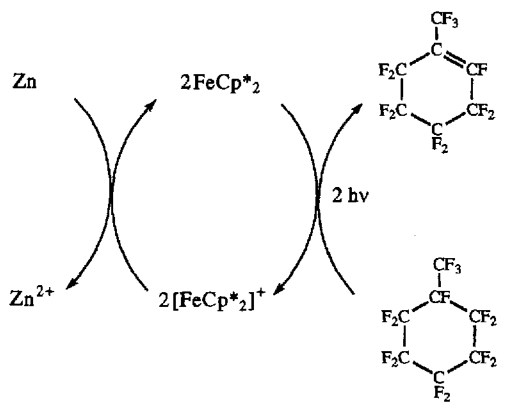


Besides perfluoroarenes, perfluoroalkenes are also valuable compounds, and methods to obtain them from the readily available perfluoroalkanes are of great interest. Since they readily react with nucleophiles, nonnucleophilic reducing agents must be used. A new stoichiometric and catalytic reaction has recently been reported from our group in which decamethylferrocene ($FeCp^*_2$) can react with perfluoroalkanes with tertiary centers to give perfluoroalkenes under UV irradiation and in the presence of a fluoride acceptor salt such as LiO_3SCF_3, when $FeCp^*_2$ is oxidized to $FeCp_2^{*+}$ (Scheme 10). The starting ferrocene can be regenerated using Zn(0), making the process catalytic (Scheme 11). In order to obtain the perfluoroalkenes, an excess of saturated perfluorocarbon is used because overreduction starts to occur if the conversion is pushed too far. The alkene product is not easily separated from the excess of alkane, however, and so it is used in situ for further reactions and the final product is isolated[70].

Scheme 10



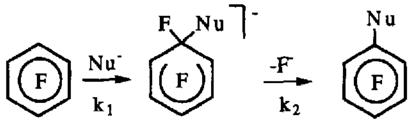
Scheme 11. Photocatalytic defluorination of perfluoromethylcyclohexane by FeCp$^*_2$



Activation of Aromatic and Vinylic C–F Bonds

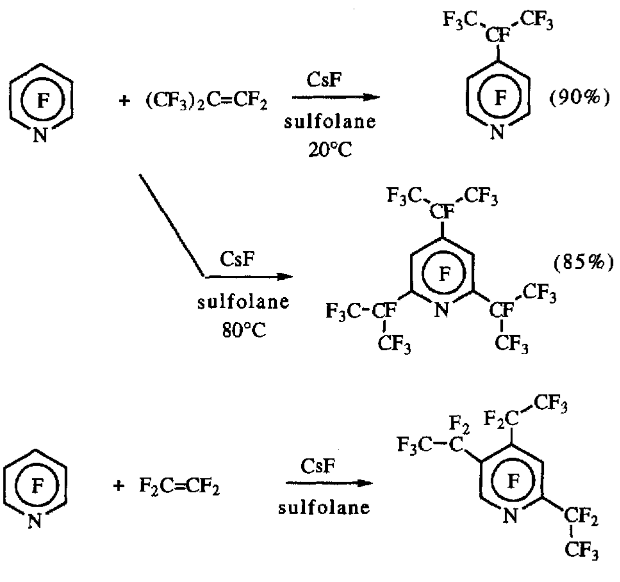
Highly fluorinated aromatic compounds can undergo nucleophilic aromatic substitutions and a large number of derivatives has been synthesized by this classical route (Scheme 1)[50]. This pathway is favored because their electron-withdrawing substituents stabilize the negative charge in the intermediate, and a good leaving group, the fluoride ion, is present. The generally accepted pathway for this reaction involves a two-step mechanism (Scheme 12)[71].

Scheme 12

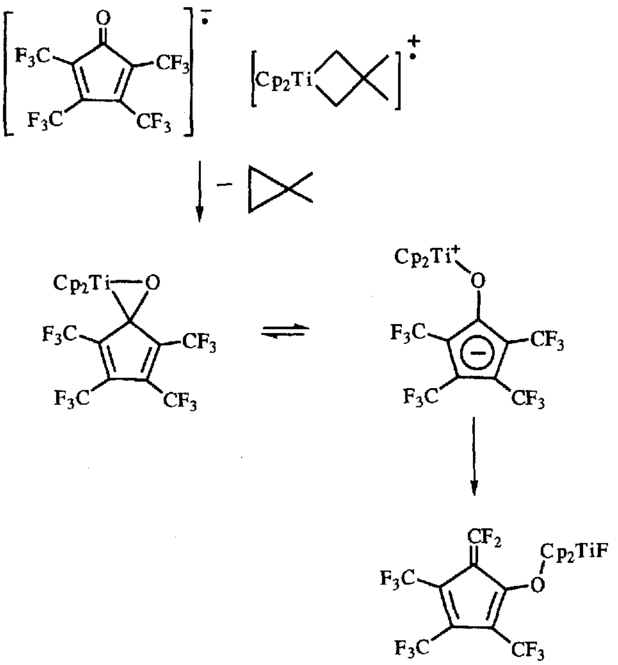


Although aromatic hydrocarbons readily undergo electrophilic aromatic substitution, polyfluoroarenes tend to give nucleophilic aromatic substitutions. A nucleophilic equivalent of the Friedel-Crafts alkylation of perfluoroarenes operates when an intermediate perfluoroalkyl carbanion, formed by attack of a fluoride ion on a perfluoroalkene, reacts with a perfluoroarene (Scheme 13)[72].

Scheme 13



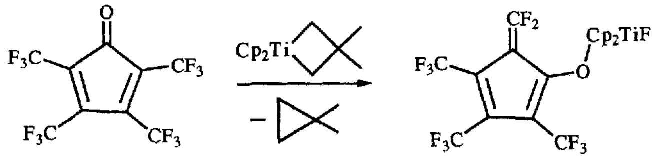
Scheme 15. Proposed radical mexhanism involving charge transfer



Many reactions of perfluoroarenes with metal complexes have also been reported. One of the earliest examples was the reaction between C_6F_6 and the low-valent nickel metal complex $Ni(PEt_3)_2(COD)$ to give *trans*-$Ni(PEt_3)_2(C_6F_5)(F)$, which is thought to occur by an SN_{Ar} mechanism[73]. Activation of C–F bonds in fluoroaromatic compounds by metal centers can be carried out by electron-deficient or electron-rich metal complexes and transition-metal ions.

Heterocyclic cleavage of C–F bonds by electron-deficient transition metals has also been observed, but this pathway is relatively uncommon[74]. The driving force for the reaction in these cases is the high fluorophilicity of the metal center. Burk et al. showed that tetrakis(trifluoromethyl) cyclopentadienone reacts at –20°C with bis(cyclopentadienyl) titanacyclobutanes to affort a titanium fluoride complex (Scheme 14).

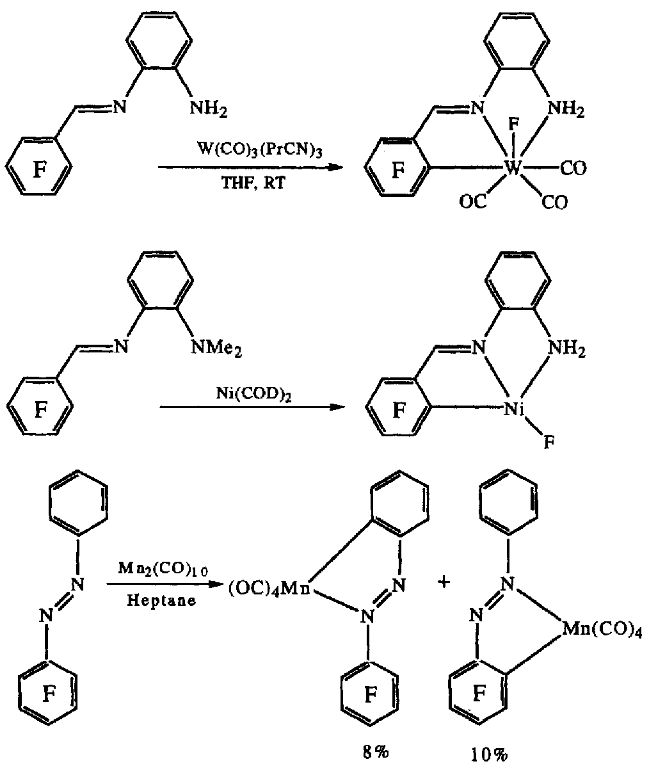
Scheme 14



The authors proposed an electron-transfer mechanism to account for the observed products (Scheme 15)[75].

Both intra- and intermolecular activation of C–F bonds by electron-rich metal centers have been widely studied. Intramolecular aromatic C–F bond activation by transition-metal centers such as W, Mo, Mn, Pt and Ni can occur under mild conditions. Some examples can be seen in Scheme 16[76].

A recent example of intermolecular C–F activation by an electron-rich metal complex involves $[Ru(dmpe)_2H_2]$, Scheme 16



which reacts with C_6F_6 at low temperature to give *trans*-[Ru(dmpe)$_2$(C_6F_5)(H)] (Scheme 17). Interestingly, photolysis of the metal complex was not necessary for the reaction to occur.

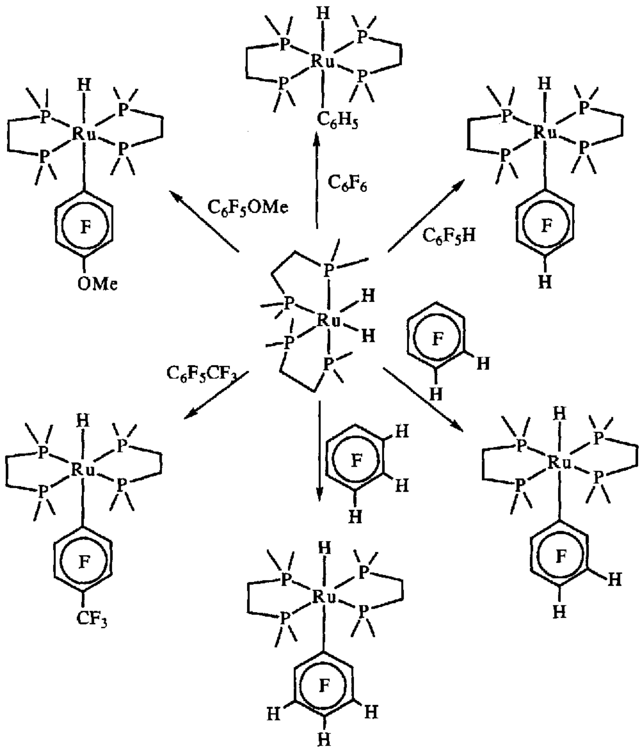
Scheme 17. Proposed mechanism for the reaction of *cis*-[Ru(dmpe)$_2$H$_2$] with fluoroarenes

$$L_4RuH_2 + C_6F_6 \longrightarrow [L_4RuH_2]^{\bullet +}\,[C_6F_6]^{\bullet -} \xrightarrow{-HF}$$

$$[L_4RuH]^{\bullet}\,[C_6F_5]^{\bullet} \longrightarrow [L_4Ru(H)(C_6F_5)]$$

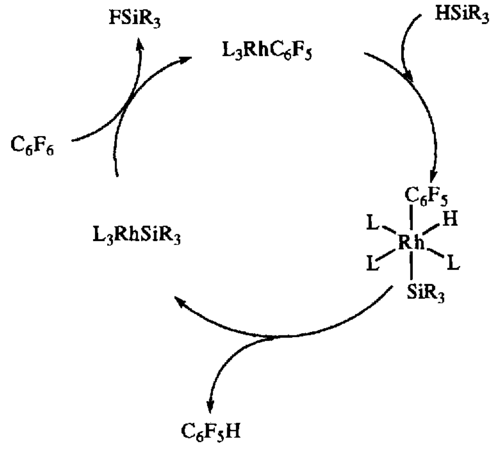
This complex also reacts with C_6F_5H and $C_6F_4H_2$, and selective activation of C−F bonds was observed in all cases (Scheme 18). X-ray and spectroscopic studies indicated that a *trans* product Ar−Ru−H is obtained in all the cases studied. Of the three possible mechanisms considered by the authors − nucleophilic substitution, oxidative addition and electron transfer − only the last seems likely. Nucleophilic substitution was discarded because of the very mild conditions and the low nucleophilicity of [Ru(dmpe)$_2$H$_2$]. Oxidative addition seemed unlikely because: (a) this reaction pathway might be expected to give a *cis* product, and (b) [Ru(dmpe)$_2$], thermally generated from [Ru(dmpe)$_2$(naphthyl)H], did not react with C_6F_6 even at 70°C[77].

Scheme 18. Reaction of *cis*-[Ru(dmpe)$_2$H$_2$] with fluoroarenes



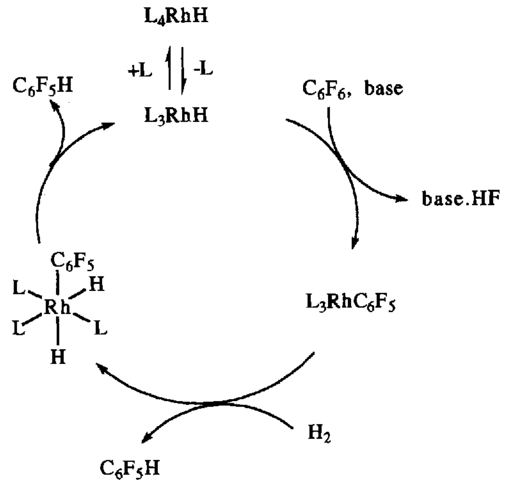
Aizenberg and Milstein have used the oxidative addition pathway in the first catalytic activation of C−F bonds by transition-metal complexes under mild conditions. [Rh(PMe$_3$)$_3$(SiR$_3$)] (R$_3$ = Ph$_3$ or PhMe$_2$), synthesized from [Rh(PMe$_3$)$_3$(Cl)] and LiSiR$_3$, catalyzes the reaction of C_6F_6 with Ph$_3$SiH or (EtO)$_3$SiH at room temperature to give C_6F_5H. Some activation of the C−F bond also occurs with C_6F_5H, but C−H bond activation is preferred. The thermodynamic driving force of the reaction is clearly the formation of a very strong Si−F bond (Scheme 19)[78].

Scheme 19. Catalytic cycle for hydrogenation of hexafluorobenzene with hydrosilanes



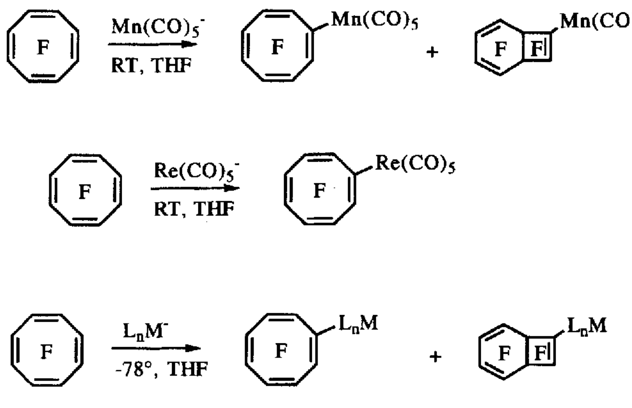
Catalytic substitution of F by H was also obtained on reaction of C_6F_6 and H_2 with Rh(PMe$_3$)$_3$H (Scheme 20), if the HF formed was removed with triethylamine[79]. One of the key features of these catalytic reactions is the geometry of the ligands in the coordination sphere. The C_6F_5 group is located *trans* to either R$_3$Si- or H-; their both being high *trans*-effect ligands may facilitate the C−H bond formation in the reductive elimination step.

Scheme 20. Catalytic cycle for hydrogenation of hexafluorobenzene



Transition metal complex anions can also activate C–F bonds, and a mechanism involving nucleophilic displacement of fluoride to give a metal-arene or metal-vinyl complex has been proposed. In an early study by King and Bisnette, hexafluorobenzene was found to react with $CpFe(CO)_2^-$ to give $CpFe(CO)_2(C_6F_5)$ by displacement of the fluoride ion[80]. Other carbonyl anion complexes, such as $Na[Mn(CO)_5]$, $Na[Re(CO)_5]$, $K[CpRu(CO)_2]$, $K[CpFe(CO)_2]$, and $K[Cp^*Fe(CO)_2]$, can also react with unsaturated fluorocarbons by the same mechanism (Scheme 21)[81].

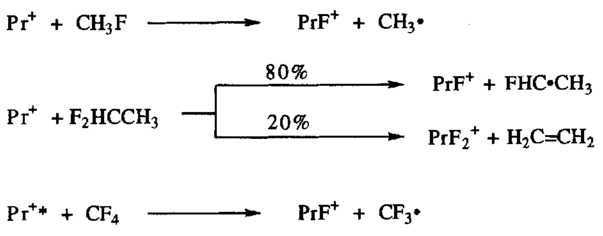
Scheme 21



(L_nM^- = $CpFe(CO)_2$, $Cp^*Fe(CO)_2$, or $CpRu(CO)_2$)

Lanthanide complexes of the type $LnCp_2^*$ (Ln = Eu, Sm, Yb) have been shown to activate C–F bonds homolytically[82]. An actinide complex, $[(MC_5H_4)U(t\text{Bu})]$, has been shown to react with perfluoroalkanes by a radical mechanism[83]. Very recently, the praseodymium cation has been shown to react in the gas phase with fluorocarbons by an unexpected homolytic mechanism (Scheme 22)[48].

Scheme 22



(Pr = Praseodymium)

Conclusions and Future Prospects

The principles governing the activation of C–F bonds are beginning to emerge from recent studies. New ways of making fluorinated derivatives may begin to have an impact on the fluorochemical industry. Some of these methods may also find important environmental applications in the destruction of halocarbons. Just as in C–H activation chemistry overoxidation can be a serious problem, in C–F activation overreduction can prevent the formation of useful products. Only a few years ago it was thought that fluoroalkanes would only react under forcing conditions; we now see that new mechanistic pathways can provide mild routes for reactions, which should allow higher selectivities to be achieved. Further developments along these lines and advances in the conceptual framework are likely in the near future.

We thank the *DOE* (RHC), the *3M Company* (JB) and the *Fonds zur Förderung der Wissenschaftlichen Forschung* (BJ) for support.

---

[1] *Organofluorine Chemistry, Principles and Commercial Applications* (Eds.: R. E. Banks, B. E. Smart and J. C. Tatlow), Plenum, NY, **1994**.
[2] [2a] R. H. Crabtree, *Chem. Rev.* **1985**, *85*, 145–269. – [2b] R. H. Crabtree, *Angew. Chem. Int. Ed. Engl.* **1993**, *32*, 789–805.
[3] A. R. Ravishankara, S. Solomon, A. A. Turnipseed, R. F. Warren, *Science* **1993**, *259*, 194–199.
[4] Intergovernmental Panel on Climate Change, *Climate Change – The IPCC Scientific Assessment*, Cambridge U. Press, Cambridge, **1990**.
[5] [5a] J. L. Kiplinger, T. G. Richmond, C. E. Osterberg, *Chem. Rev.* **1994**, *94*, 373–431. – [5b] R. P. Hughes, *Adv. Organomet. Chem.* **1990**, *31*, 183–267. – [5c] N. M. Doherty, N. W. Hoffman, *Chem. Rev.* **1991**, *91*, 553–573. – [5d] R. J. Kulawiec, R. H. Crabtree, *Coord. Chem. Rev.* **1990**, *99*, 89–115.
[6] M. Hudlicky, *Chemistry of Organic Fluorine Compounds*, Macmillan Co., NY, **1962**, pp. 288–298.
[7] B. E. Smart in *The Chemistry of Halides, Pseudo-Halides and Azides* (Eds.: S. Patai, Z. Rappoport), Wiley, NY, **1983**, Supplement D, pp. 604–606.
[8] L. Pauling, *Nature of the Chemical Bond*, 3rd ed., Cornell Univ. Press, Ithaca, NY, **1960**, pp. 314–316.
[9] [9a] L. Radom, W. J. Hehre, J. A. Pople, *J. Am. Chem. Soc.* **1971**, *93*, 289–300. – [9b] L. Radom, P. J. Stiles, *Tetrahedron lett.* **1975**, *10*, 789–792.
[10] M. Hudlicky, *Chemistry of Organic Fluorine Compounds*, Macmillan Co., NY, **1962**, pp. 288–303.
[11] [11a] R. P. Geyer, *N. Engl. J. Med.* **1973**, *289*, 1077. – [11b] R. P. Geyer, R. C. Monroe, K. Taylor, *Fed. Proc.* **1973**, *32*, 1927.
[12] J. G. Riess, M. Le Blanc, *Angew. Chem. Int. Ed. Engl.* **1978**, *17*, 621–634.
[13] [13a] D. P. Carlson, W. Schmiegel, *Ullman's Encyclopedia of Industrial Chemistry*, 5th ed., Wiley, NY, Vol A11, pp. 393–429. – [13b] S. V. Gangal, *Encyclopedia of Polymer Science and Engineering*; Wiley, NY, **1989**, Vol. *16*.
[14] M. Hudlicky, *Chemistry of Organic Fluorine Compounds*, Macmillan Co., NY, **1962**, pp. 304–306.
[15] I. T. Horvath, J. Rabai, *Science* **1994**, *266*, 72–75.
[16] A. Yokozeki, S. H. Bauer, *Topics Curr. Chem.* **1975**, *53*, 71–119.
[17] R. D. Chambers, *Fluorine in Organic Chemistry*, Wiley, NY, **1973**, chapter 5, pp. 97–108.

[18] [18a] J. Banus, H. J. Emeleus, R. N. Haszeldine, *J. Chem. Soc.* **1951**, 60–64. – [18b] R. D. Chambers, W. K. R. Musgrave, J. Savory, *J. Chem. Soc.* **1961**, 3779–3786.

[19] D. P. Stevenson, G. M. Coppinger, *J. Am. Chem. Soc.* **1962**, *84*, 149–152.

[20] [20a] S. Chowdhury, E. P. Grimsrud, T. Heinis, P. Kebarle, *J. Am. Chem. Soc.* **1986**, *108*, 3630–3635. – [20b] P. S. Drzaic, J. Marks, J. I. Brauman in *Gas Phase Ion Chemistry*, Vol. *3*, (Ed.: M. T. Bowers), Academic Press, Orlando, **1984**, p. 167.

[21] R. J. Kulawiek, R. H. Crabtree, *Coord. Chem. Rev.* **1990**, *99*, 89–115.

[22] [22a] R. D. Chambers, *Fluorine in Organic Chemistry*, Wiley, NY, **1973**, Ch. 5, pp. 274–308. – [22b] M. J. Burk, D. L. Staley, W. J. Tumas, *J. Chem. Soc., Chem. Commun.* **1990**, 809–810.

[23] [23a] E. W. Schlag, W. B. Peatman, *J. Am. Chem. Soc.* **1964**, *86*, 1676–1679. – [23b] E. W. Schlag, E. W. Kaiser, *J. Am. Chem. Soc.* **1965**, *87*, 1171–1174.

[24] R. H. Crabtree, *The Organometallic Chemistry of the Transition Metals*, 2nd ed., J. Wiley & Sons, NY, **1994**, p. 110.

[25] M. R. C. Gerstenberger, A. Haas, *Ang. Chem. Int. Ed. Engl.* **1981**, *20*, 647–667.

[26] L. A. Bigelow in *Fluorine Chemistry* (Ed.: H. Simons), Academic, NY, **1970**, Vol. 1, p. 373.

[27] [27a] W. K. R. Musgrave, F. Smith, *J. Chem. Soc.* **1949**, 3021–3026. – [27b]W. K. R. Musgrave, F. Smith, *J. Chem. Soc.* **1949**, 3026–3028. – [27c] R. N. Haszeldine, F. Smith, *J. Chem. Soc.* **1950**, 2689–2694. – [27d] R. N. Haszeldine, F. Smith, *J. Chem. Soc.* **1950**, 2787–2789.

[28] [28a] A. K. Barbour, G. B. Barlow, J. C. Tatlow, *J. Appl. Chem.* **1952**, *2*, 127–130. – [28b] R. N. Haszeldine, F. Smith, *J. Chem. Soc.* **1950**, 3617–3623.

[29] J. H. Simons in *Fluorine Chemistry*, Academic, NY, **1950**, Vol. 1, p. 401.

[30] [30a] H. M. Scholberg, H. G. Brice, *U. S. Pat.* 2.717.871, **1955**. – [30b] T. Gramstad, R. N. Haszeldine, *J. Chem. Soc.* **1956**, 173–180.

[31] [31a] B. Gething, C. R. Patrick, M. Stacey, J. C. Tatlow, *Nature* **1959**, *183*, 588–589. – [31b] G. Gething, C. R. Patrick, B. J. K. Smith, J. C. Tatlow, *J. Chem. Soc.* **1962**, 190–193.

[32] [32a] C. W. Tullock, D. D. Coffman, *J. Org. Chem.* **1960**, *25*, 2016. – [32b] R. D. Chambers, J. Hutchinson, W. K. R. Musgrave, *Proc. Chem. Soc.* **1964**, 83; *J. Chem. Soc.* **1964**, 3573–3576. – [32c] H. C. Fielding, L. P. Gallimore, H. L. Roberts, B. Tittle, *J. Chem. Soc. (C)*, **1966**, 2142–2144.

[33] Dehalogenation: [33a] R. N. Haszeldine, *J. Chem. Soc.* **1952**, 4423–4441. – [33b] A. L. Henne, W. Postelneck, *J. Am. Chem. Soc.* **1955**, *77*, 2334–2335. – [33c] R. G. Banks, R. N. Haszeldine, J. B. Walton, *J. Chem. Soc.* **1963**, 5581–5583; Dehydrohalogenation: [33d] A. K. Barbour, H. D. MacKenzie, M. Stacey, J. C. Tatlow, *J. Appl. Chem.* **1954**, *4*, 347.

[34] [34a] J. D. LaZerte, L. J. Hals, T. S. Reid, G. H. Smith, *J. Am. Chem. Soc.* **1953**, *75*, 4525–4528. – [34b] J. C. Tatlow, *Endeavour* **1963**, *22*, 89.

[35] R. D. Chambers, R. H. Mobbs, *Adv. Fluorine Chem.* **1965**, *4*, 50.

[36] [36a] M. Green, R. B. L. Osborn, A. J. Rest, F. G. A. Stone, *J. Chem. Soc. (A)* **1968**, 2525–2530. – [36b] B. L. Booth, R. N. Haszeldine, N. I. Tucker, *J. Organomet. Chem.* **1968**, *11*, P5–P6.

[37] [37a] R. D. Chambers, R. H. Moobs, *Adv. Fluorine Chem.* **1965**, *4*, 50. – [37b] L. S. German, I. L. Knunyantz, *Angew. Chem. Int. Ed. Engl.* **1969**, *8*, 349–356. – [37c] G. A. Olah, Y. K. Mo, *J. Org. Chem.* **1972**, *37*, 1028–1034.

[38] W. A. Sheppard, C. M. Sharts, *Organic Fluorine Chemistry*, Benjamin, NY, **1969**, p. 203.

[39] J. Harmon, *U. S. Pat.* 2.404.374, **1946**; *Chem. Abs.* **1946**, *40*, 7234.

[40] [40a] D. D. Coffman, P. L. Barrick, R. D. Cramer, M. S. Raasch, *J. Am. Chem. Soc.* **1949**, *71*, 490–496. – [40b] J. L. Anderson, R. E. Putnam, W. H. Sharkey, *J. Am. Chem. Soc.* **1961**, *83*, 382–385.

[41] W. J. Middleton, W. H. Sharkey, *J. Am. Chem. Soc.* **1959**, *81*, 803–804.

[42] W. J. Middleton, *U. S. Pat.* 2831835, **1958**.

[43] H. Bürger, S. Sommer, *J. Chem. Soc., Chem. Commun.* **1991**, 456–458.

[44] *German Pat.* 1126388, 1126390, **1962**; *Chem. Abs.* **1962**, *58*, 6860, 10235.

[45] H. C. Clark, R. J. Puddephatt, *J. Chem. Soc., Chem. Commun.* **1970**, 92–93.

[46] [46a] J. F. Harris, *U. S. Pat.* 2.923.746. **1960**; *Chem. Abs.* **1962**, *57*, 7465. – [46b] J. L. Boston, D. W. A. Sharp, G. Wilkinson, *J. Chem. Soc.* **1962**, 3488–3498. – [46c] H. C. Brown, H. L. Gewanter, *J. Org. Chem.* **1960**, *25*, 2071–2072.

[47] R. D. Chambers, W. K. Musgrave, S. Partington, *J. Chem. Soc., Chem. Commun.* **1970**, 1050–1051.

[48] C. Heinemann, N. Goldberg, I. C. Tornieporth-Oetting, T. M. Klapötke, H. Schwarz, *Angew. Chem. Int. Ed. Engl.* **1995**, *34*, 213–217.

[49] W. D. Jones, F. J. Feher, *J. Am. Chem. Soc.* **1984**, *106*, 1650–1663.

[50] A. K. Barbour, M. W. Buxton, G. Fuller, *Kirk-Othmer Encyclopedia of Chemical Technology*, 2nd ed., Vol. *9*, **1966**, pp. 775–802.

[51] R. D. Chambers, *Fluorine in Organic Chemistry*, Wiley, NY, **1973**, chapter 5, pp. 274–308.

[52] J. H. Simons, L. P. Block, *J. Am. Chem. Soc.* **1937**, *59*, 1407.

[53] [53a] J. F. Miller, M. Hunt, E. T. McBee, *Anal. Chem.* **1947**, *19*, 148–149. – [53b] by Commodore Chemical Co. of Columbus Ohio, USA.

[54] L. White, O. K. Rice, *J. Am. Chem. Soc.* **1947**, *69*, 267–270.

[55] A. V. Grosse, G. H. Cady, *Ind. Eng. Chem.* **1947**, *39*, 367–369.

[56] W. R. James, W. H. Pearlson, J. H. Simons, *J. Am. Chem. Soc.* **1950**, *72*, 1761–1764.

[57] [57a] T. J. Brice, W. H. Pearlson, J. H. Simons, *J. Am. Chem. Soc.* **1949**, *71*, 2499–2501. – [57b] E. E. Lewis, M. A. Naylor, *J. Am. Chem. Soc.* **1947**, *69*, 1968–1972.

[58] R. H. Crabtree, *Chem. Rev.* **1985**, *85*, 245–269.

[59] [59a] B. Gething, C. R. Patrick, M. Stacey, J. C. Tatlow, *Nature* **1959**, *183*, 588–589. – [59b] B. Gething, C. R. Patrick, J. C. Tatlow, R. E. Banks, A. K. Barbour, A. E. Tipping, *Nature* **1959**, *183*, 586–589.

[60] D. D. MacNicol, C. D. Roberston, *Nature* **1988**, *332*, 5961–5962.

[61] N. Chakrabarti, J. Jacobus, *Macromolecules* **1988**, *21*, 3011–3014.

[62] J. A. Marsella, A. G. Gilicinski, A. M. Coughlin, G. P. Pez, *J. Org. Chem.* **1992**, *57*, 2856.

[63] B. K. Bennett, R. G. Harrison, T. G. Richmond, *J. Am. Chem. Soc.* **1994**, *116*, 11165–11166.

[64] J. L. Kiplinger, T. G. Richmond, *J. Am. Chem. Soc.* **1996**, *118*, 1805–1806.

[65] [65a] M. E. Napier, P. C. Stair, *J. Vac. Sci. Technol. A* **1991**, *9*, 649–652. – [65b] M. E. Napier, P. C. Stair, *J. Vac. Sci. Technol. A* **1992**, *10*, 2702–2708.

[66] B. E. Smart, W. J. Middleton, W. B. Farnham, *J. Am. Chem. Soc.* **1986**, *108*, 4905–4907.

[67] [67a] J. Burdeniuc, R. H. Crabtree, *Science* **1996**, *271*, 340–341. – [67b] The reaction temperatures reported in ref.[67a] are too low: aromatization requires 425 °C and mineralization requires 470 °C.

[68] [68a] S. H. Brown, R. H. Crabtree, *J. Am. Chem. Soc.* **1989**, *111*, 2935–2946. – [68b] C. A. Muedas, R. R. Ferguson, S. H. Brown, R. H. Crabtree, *J. Am. Chem. Soc.* **1991**, *113*, 2233–2242. – [68c] D. Michos, C. A. Sassano, P. Krajnik, R. H. Crabtree, *Angew. Chem. Int. Ed. Engl.* **1993**, *32*, 1491–1492. – [68d] P. Krajnik, D. Michos, R. H. Crabtree, *New J. Chem.* **1993**, *17*, 805–813. – [68e] P. Krajnik, R. H. Crabtree, *Inorg. Chem.* **1993**, *32*, 1028–1029. – [68f] P. Krajnik, R. H. Crabtree, *New J. Chem.* **1993**, *17*, 559–566.

[69] J. Burdeniuc, W. Chupka, R. H. Crabtree, *J. Am. Chem. Soc.* **1995**, *117*, 10119–10120.

[70] J. Burdeniuc, R. H. Crabtree, *J. Am. Chem. Soc.* **1996**, *118*, 2525–2526.

[71] J. Burdeniuc, *Thesis*, Yale University, **1996**.

[72] [72a] S. L. Bell, R. D. Chambers, M. Y. Gribble, J. R. Maslakiewicz, *J. Chem. Soc., Perkin 1* **1973**, 1716–1720. – [72b] R. D. Chambers, M. Y. Gribble, *J. Chem. Soc., Perkin 1* **1973**, 1405–1410.

[73] D. R. Fahey, J. E. Mahan, *J. Am. Chem. Soc.* **1977**, *99*, 2501–2508.

[74] J. A. Morrison, *Adv. Organomet. Chem.* **1993**, *35*, 211–218.

[75] M. J. Burk, D. L. Staley, W. J. Tumas, *J. Chem. Soc., Chem. Commun.* **1990**, 809–810.

[76] [76a] T. G. Richmond, *Coord. Chem. Rev.* **1990**, *105*, 221–250. – [76b] C. E. Osterberg, T. G. Richmond, *ACS Symp. Ser.* **1994**, *555*, 392–404. – [76c] M. I. Bruce, B. L. Goodall, G. L. Sheppard, F. G. Stone, *J. Chem. Soc., Dalton Trans.* **1975**, 591–595.

[77] M. K. Whittlesey, R. N. Perutz, M. H. Moore, *J. Chem. Soc., Chem. Commun.* **1996**, 787–788.

[78] M. Aizenberg, D. Milstein, *Science* **1994**, *265*, 359–360.

[79] M. Aizenberg, D. Milstein, *J. Am. Chem. Soc.* **1995**, *117*, 8674–8675.

[80] R. B. King, M. B. Bisnette, *J. Organomet. Chem.* **1964**, *2*, 38–48.

[81] [81a] R. P. Hughes, R. T. Carl, S. J. Doig, R. C. Hemond, D. E. Sankoff, W. L. Smith, L. C. Stewart, R. E. Davis, K. D. Holland, P. Dickens, R. P. Kashyap, *Organometallics* **1990**, *9*, 2732–2745. – [81b] S. J. Doig, R. P. Hughes, S. L. Patt, D. E. Samkoff, W. L. Smith, *J. Organomet. Chem.* **1983**, *250*, C1–C4. – [81c] S. J. Doig, R. P. Hughes, R. E. Davis, S. M. Gadol, K. D. Holland, *Organometallics* **1984**, *3*, 1921–1922. – [81d] R. P. Hughes, S. J. Doig, R. C. Hemond, W. L. Smith, R. E. Davis, S. M. Gadol, K. D. Holland, *Organometallics* **1990**, *9*, 2745–2753.

[82] P. L. Watson, T. H. Tulip, I. Williams, *Organometallics* **1990**, *9*, 1999–2009.

[83] M. Weydert, R. A. Andersen, R. G. Bergman, *J. Am. Chem. Soc.* **1993**, *115*, 8837–8838.

[96184]