



Title	Chemical Strategies for the Cleavage of the C(sp ³)-F Bonds in Perfluoroalkyl Groups
Author(s)	Doi, Ryohei; Ogoshi, Sensuke
Citation	European Journal of Organic Chemistry. 2024, 27(11), p. e202301229
Version Type	VoR
URL	https://hdl.handle.net/11094/95268
rights	This article is licensed under a Creative Commons Attribution 4.0 International License.
Note	

The University of Osaka Institutional Knowledge Archive : OUKA

<https://ir.library.osaka-u.ac.jp/>

The University of Osaka

Chemical Strategies for the Cleavage of the C(sp³)–F Bonds in Perfluoroalkyl Groups

Ryohei Doi*^[a] and Sensuke Ogoshi*^[a]

Perfluoroalkyl substances (PFAS) have been recognized as environmental pollutants. Hence, their efficient and mild destruction is a significant research interest. While many research articles and review papers have reported the cleavage of the C(sp²)–F bonds, single C(sp³)–F bond, and CF₃ groups in PFAS, in this study, limited and emerging examples of a longer perfluoroalkyl group containing at least one repeating

unit of 1,1,2,2-tetrafluoroethylene was focused. In this *Concept*, we summarized recent progress on the chemical defluorination of PFAS via the cleavage of unactivated C(sp³)–F bonds in longer perfluoroalkyl groups under mild conditions (~150 °C). In addition to classical reductive defluorination, strategies featuring Lewis acid activation and the transient generation of an unsaturated bond were described.

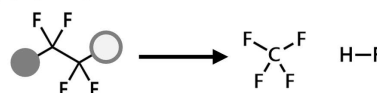
1. Introduction

Although the widespread use of per- and polyfluoroalkyl substances (PFAS) significantly contributes to establishing our affluent society, these chemicals are currently identified as environmental pollutants.^[1,2] In fact, chemical companies produce various PFAS for numerous applications, some of which are released into the environment.^[3] The high strength of the multiple C(sp³)–F bonds in PFAS is attributed to their outstanding thermal and chemical stabilities, thereby making them resistant to environmental degradation.^[4] Therefore, the released PFAS and their partial degradation products can lead to long-term environmental pollution.^[5] The strict regulations,^[2] appropriate use and recovery, and advanced adsorption technologies^[6] of PFAS would lead to the storage of this class of chemical wastes. As a responsibility for the future generation, chemists should pursue mild and environmentally friendly methods to destroy PFAS.

Several technologies have been developed for the remediation of PFAS. Incineration of PFAS has been applied to the treatment of wastewater (Figure 1A).^[7] However, incineration exhibits significant concerns, such as the requirement of high temperatures (> 1000 °C) and formation of products of incomplete combustion, including small perfluoroalkanes (e.g., CF₄) exhibiting extremely high stability and the greenhouse effect. Recently, hydrothermal methods have emerged as an efficient technique for destroying PFAS. For example, Hori and co-workers reported a pioneering study in which hot water was used to decompose PFAS with the aid of iron powder.^[8] Instead

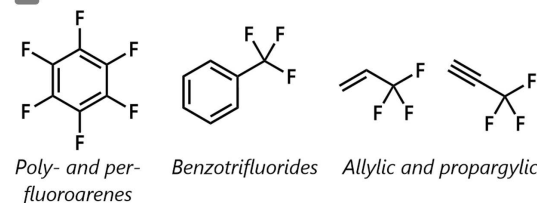
A. Major degradation methods of PFAS

(Hydro)thermal Methods



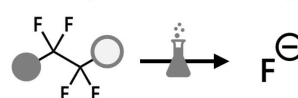
- High temperature, pressure, and energy input
- Safety concerns: e.g., corrosive HF formation

Chemical Methods



- Well-studied functional groups: Arenes, alkenes and CF₃

B. The scope of this Concept paper



- Chemical defluorination of longer perfluoroalkyls under mild conditions

C. Selected strategies

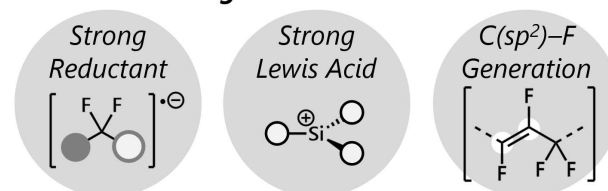


Figure 1. Degradation methods for PFAS.

[a] Dr. R. Doi, Prof. S. Ogoshi
Department of Applied Chemistry, Faculty of Engineering
Osaka University
Suita, Osaka 565-0871, Japan
E-mail: rdoi@chem.eng.osaka-u.ac.jp
ogoshi@chem.eng.osaka-u.ac.jp

© 2024 The Authors. European Journal of Organic Chemistry published by Wiley-VCH GmbH. This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

of a detailed discussion of this technology, which can be found in recent comprehensive review papers,^[9] the intrinsic problem

of this method is briefly described as follows: The reaction operating at an extremely high pressure (~200 bar) necessitates high energy and instrumental costs, as well as the risk of explosive incidents. In addition, the reaction mixture contains notorious hydrogen fluoride, which is derived from PFAS to be decomposed. Although NaOH is hazardous upon spillover, its addition to neutralize hydrogen fluoride is examined.^[10–13] Therefore, even though the technology can be state-of-the-art for practical applications, developing a PFAS destruction method under relatively low pressures (1–2 bar) and temperatures (~150 °C) is still imperative.

Herein, the recent progress of chemical defluorination methods under mild conditions is discussed, as shown in Figure 1. The cleavage of the C(sp³)–F bonds at activated positions, such as the benzylic, allylic, and propargylic ones, is well investigated.^[14] Notably, research in this area have been described in the context of chemical synthesis rather than the destruction of pollutants.^[15,16] Although CF₂- or CF₃-containing molecules are also categorized as PFAS according to the Organization for Economic Co-operation and Development, the notorious, problematic class of PFAS contains longer perfluoroalkyl chains, such as perfluorooctanoic acid (PFOA), perfluorooctanesulfonic acid, and polymers such as poly(tetrafluoroethylene) (PTFE). Therefore, herein, the chemical defluorination of PFAS via multiple cleavage reactions of the unactivated C(sp³)–F bonds in longer perfluoroalkyl groups (typically containing CF₂CF₂ units) at relatively low temperatures (~150 °C) is focused. Photochemical and electrochemical methods have been investigated for the degradation of longer PFAS; recent review papers have been referred to instead of discussing them as main topics.^[17,18] Typically, a longer perfluoroalkyl group contains CF₂ units, which are not activated by adjacent C–C or carbon–heteroatom multiple bonds. Therefore, some tricks are requested to achieve the cleavage of the C(sp³)–F bonds. These strategies are divided into three broad categories (Figure 1C): use of strong reductants, Lewis acid activation, and the transient generation of fluoroalkene, of which the cleavage of C–F bonds is more facile than that of an unactivated C(sp³)–F bond. Organizing these chemistries into one *Concept* paper is thought to help steer the future direction of this research area.

2. Electron Transfer

The reduction of longer perfluoroalkyl groups is a major defluorination strategy of these molecules. Although the perfluoroalkyl group is chemically inert, the low-lying LUMO derived from the electron-withdrawing effect of F atoms could be susceptible to reduction at low temperatures.^[19] MacNicol and Robertson reported one of the remarkable experimental examples of the complete defluorination of perfluorodecalin (**1**, a mixture of *cis* and *trans* isomers) with sodium thiophenoxide (Scheme 1A, DMEU = 1,3-dimethyl-2-imidazolidinone).^[20] The reaction, affording octakis(phenylthiol)naphthalene (**2**), was believed to involve the transfer of electrons from thiophenoxide to **1**. The other typical example involving the defluorination of perfluoroalkanes with sodium reductants below room temperature was reported by Pez and coworkers.^[21] When **1** was treated with sodium/benzophenone, perfluoronaphthalene (**3**) was obtained in a good yield (Scheme 1A). The peak reduction potentials of cyclic perfluoroalkanes and arenes in THF were measured. The reduction potential was approximately correlated to the reaction outcome: Perfluorocyclohexane (**5**) was resistant to reduction by sodium/benzophenone, while **1** smoothly afforded a defluorinated product. The perfluoroalkanes comprising a tertiary fluoride moiety were concluded to be more reactive. According to theoretical calculations, which predicted larger adiabatic electron affinity values for branched perfluoroalkanes than for linear ones, the negative hyperconjugation from σ* orbitals of the C–F bonds *trans* to the tertiary fluoride moiety would stabilize the resulting anions.^[22,23] Highly reductive metallocene complexes also promoted the defluorination of **1** to afford **3**.^[24,25] Sung and Lagow reported a unique outcome for the reduction of perfluoroether **6** (Scheme 1C).^[26] The reaction afforded perfluorodibenzofuran (**7**) instead of perfluorobiphenyl. As the reduction of perfluorobiphenyl did not produce **7**, the cyclization of a partially reduced intermediate would be involved.

The reduction of fluoropolymers, e.g., PTFE, also has been investigated in the context of surface modification to improve the physical properties of the polymer or prepare carbonaceous materials.^[27] Here, several typical reactions, which proceed at low temperatures, are introduced with a focus on the degree of defluorination. An early example, reported in 1958, involved the surface modification of PTFE with sodium naphthalenide

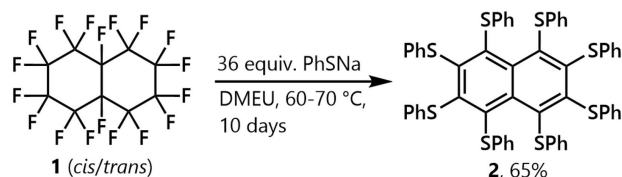


Ryohei Doi was born in 1989 in Kobe, Japan. In 2016, he received his PhD from Osaka University under the tutelage of Prof. Sensuke Ogoshi. During his postgraduate studies, he briefly joined the group of Prof. Brian M. Stoltz at the California Institute of Technology (2015). In 2016, he joined Prof. Sato's group at Hokkaido University as an Assistant Professor. In 2021, he returned to the Ogoshi group as an Assistant Professor. He is currently working on synthetic studies of organofluorine compounds using transition-metal complexes.

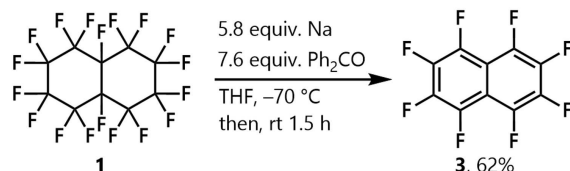


Sensuke Ogoshi received his PhD from Osaka University in 1993 under the tutelage of Prof. Shinji Murai. During his postgraduate studies, he also worked with Prof. Lanny S. Liebeskind at Emory University (1991). In the same year, he joined the faculty at Osaka University as an Assistant Professor in the group of Prof. Hideo Kurosawa. In 1999, he was promoted to an Associate Professor, and in 2007, he became Full Professor. In 1996–1997, he received a JSPS Fellowship for Research Abroad to work in the research group of Prof. Jeffery M. Stryker at the University of Alberta.

A. MacNicol and Robertson (1988)

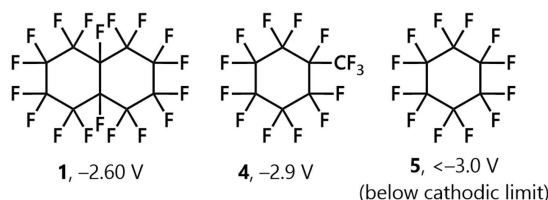


B. Pez (1992)

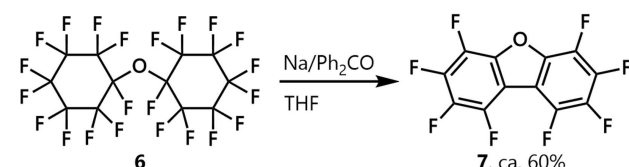


■ Other reductants: Cp_2Co , Cp_2ZrCl_2 , Cp_2TiF_2 ...

■ Reduction potential (V vs Ag/AgClO_4)



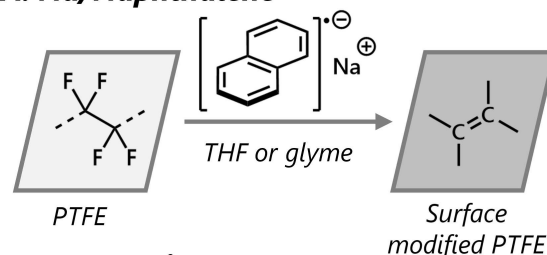
C. Sung and Lagow (1998)



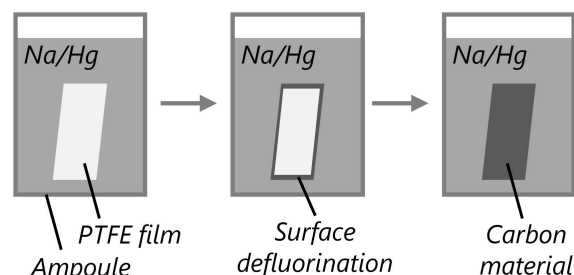
Scheme 1. Reduction of perfluoroalkyl compounds with strong reductants.

(Scheme 2A).^[28] Recently, detailed experimental and theoretical studies on the surface modification of PTFE with sodium naphthalenide in glyme were reported by Herlem and co-workers.^[29] The combined Raman spectroscopy, X-ray photoelectron spectroscopy (XPS), and infrared (IR) spectroscopy revealed C–C double-bond formation. The related observation was previously reported by Badyal and coworkers, who investigated the XPS of PTFE after the vapor deposition of sodium.^[30] Interestingly, the formation of CF_3 groups, which would be initiated by the nucleophilic attack of fluoride, was also revealed. The other well-studied reductants included sodium or lithium amalgam, which, in some cases, defluorinated PTFE completely (Scheme 2B).^[27] Reduction started at the contacting plane of amalgam and PTFE. Interestingly, the reaction further proceeded into the inner side of the PTFE foil via the formation of a short-circuited galvanic cell; in the cell, a carbon layer was generated by the reduction of PTFE, which acted as a solid electrolyte, an electron conductor, and an electrode.^[31–33] The importance of the amalgam for the complete defluorination of PTFE was implied by the experimental results reported by Hlavatý and Kavan.^[34] The reduction of PTFE powder with the alkali metal suspension (Li, Na, and K) in organic solvents such as toluene and *n*-octane afforded a carbon material containing residual F atoms. In contrast to

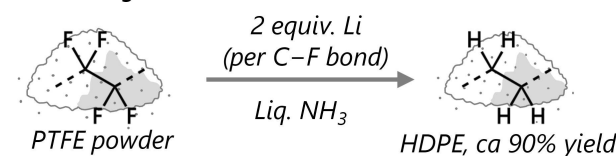
A. Na/Naphthalene



B. Na/Hg, Li/Hg



C. Li/NH₃



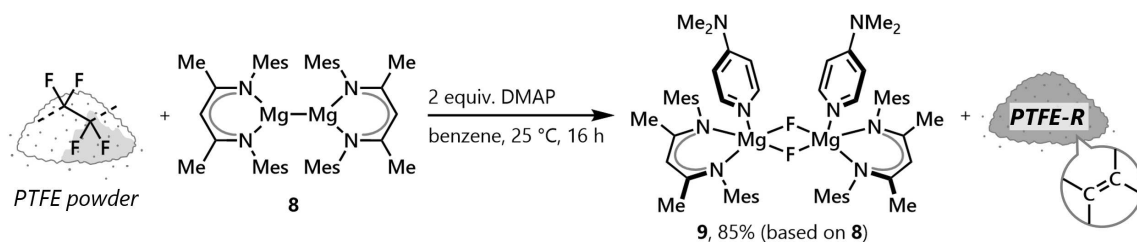
Scheme 2. Reduction of PTFE.

these reduction reactions without an unequivocal proton source, the treatment of PTFE with lithium ammonia was reported to generate high-density polyethylene (HDPE) by complete hydrodefluorination (Scheme 2C).^[35] The treatment of a 2-fold excess of lithium with respect to the number of C–F bonds with PTFE powder in liquid ammonia afforded white material, the spectroscopic data of which, including IR, solid-state ^{13}C NMR, and elemental analysis, were identical to those of HDPE.

Recently, Crimmin reported the partial reductive defluorination of PTFE using dimagnesium reagent **8** (Scheme 3).^[36] The treatment of PTFE powder with **8**, which was originally developed by Jones,^[37,38] and *N,N*-dimethylaminopyridine (DMAP) in benzene afforded magnesium fluoride complex dimer **9** at room temperature in an isolated yield of 85%. The comparison of the powder X-ray diffraction spectra of the PTFE sample and the reduced grayish material (labeled **PTFE-R** by the author) revealed that the amorphous region of PTFE was defluorinated. The IR spectrum of **PTFE-R** revealed an absorption assigned to the C–C double-bond vibrations.

3. Silylium Cation

Strong Lewis acids are known to abstract fluorine from fluoroalkanes. Generally, high Lewis acidity is required to overcome two possible obstacles: the low Lewis basicity of the lone pairs on fluorine atoms and the high bond dissociation

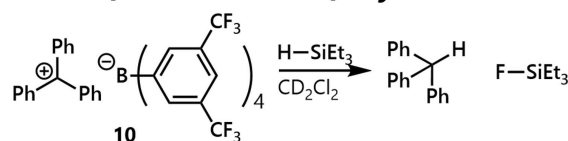


Scheme 3. Partial reduction of PTFE with a dimagnesium reagent.

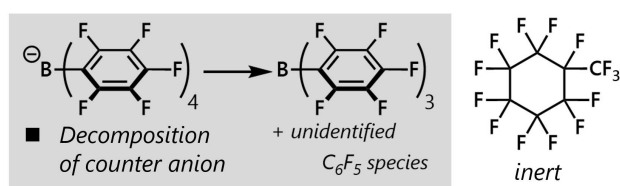
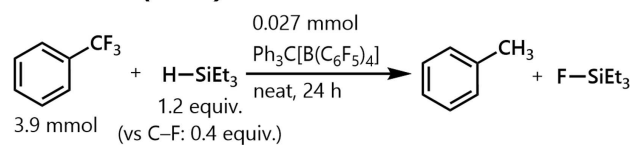
energy of a C–F bond. Silylium is one of the most successful examples of Lewis acids to abstract a fluoride ion from organofluorine compounds with the concomitant generation of the carbocation.^[39–41] Here, the hydrodefluorination of a longer perfluoroalkyl compound in the study by Ozerov is introduced, along with essential related studies. In the 1990s, trials on the preparation of silylium salt using $[\text{Ph}_3\text{C}][\text{B}\{3,5-(\text{CF}_3)_2\text{C}_6\text{H}_3\}_4]$ (**10**) were reported to lead to decomposition via Si–F bond formation (Scheme 4A).^[42,43] Later, Ozerov and coworkers reported the hydrodefluorination of aliphatic fluorocarbons using silylium salt as a catalyst (Scheme 4B).^[44] The reaction was designed as a Si–H/C–F metathesis reaction, which was

thermodynamically favorable due to the remarkable strength of the Si–F bond. The turnover number (TON) of the $[\text{Ph}_3\text{C}][\text{B}(\text{C}_6\text{F}_5)_4]$ catalyst precursor, which would produce an active silylium or silylium-like species, reached 126 for the reaction of PhCF_3 with Et_3SiH . In this study, the counteranion $[\text{B}(\text{C}_6\text{F}_5)_4]^-$ decomposed during hydrodefluorination. Notably, in this reaction system, perfluoromethylcyclohexane was inert. Then, Ozerov and coworkers discovered that using carborane as a counteranion enhanced the TON and enabled difficult transformations, including the hydrodefluorination of 1,1,1,2,2,3,3,4,4-nonafluorohexane (**11**) (Scheme 4C).^[45] As the reaction proceeded via the generation of a carbocation-like intermediate, skeletal rearrangement occurred, affording some branched hydrocarbons.

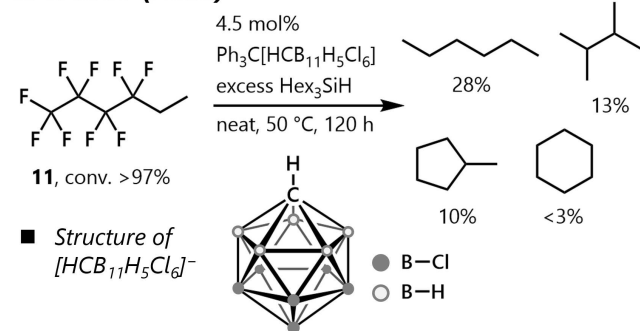
A. Trial for observation of silylium cation



B. Ozerov (2005)



C. Ozerov (2008)

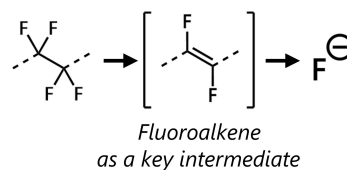


Scheme 4. Lewis acid strategy and its application to the hydrodefluorination of a longer perfluoroalkyl group.

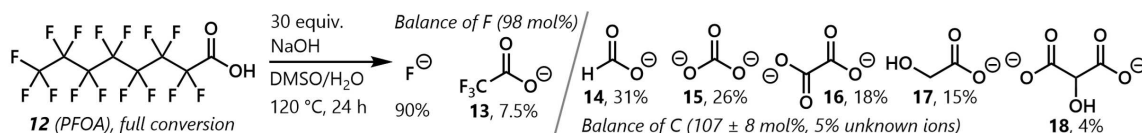
4. Transient fluoroalkene generation

Here, a strategy enabling the degradation of longer perfluoroalkyl compounds via the transient generation of a fluoroalkene is proposed (Scheme 5). The cleavage of the C–F bond in fluoroalkenes is more susceptible than that in fluoroalkanes in the presence of metal complexes or nucleophiles due to the presence of π -systems, which accept electrons to induce the elimination of F. Therefore, the transient generation of a fluoroalkene moiety in a longer perfluoroalkyl group is an effective strategy for defluorination. The incorporation of the regeneration step of the fluoroalkene moiety would lead to a continuous process that ends with complete defluorination.

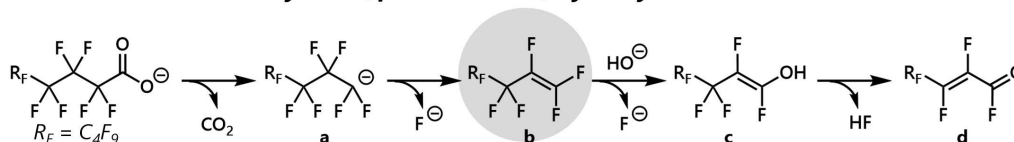
Dichtel, Houk and coworkers disclosed an operationally simple method for the decomposition of perfluoroalkyl carboxylic acids by treating them with NaOH in dimethyl sulfoxide (Scheme 6A).^[46] The reaction was conducted at 120 °C to foster the rate-limiting decarboxylation step. After heating a DMSO/ H_2O solution of PFOA (**12**) for 24 h with 30 equiv. of NaOH (2 equiv. vs C–F bond), 90% of fluorine was obtained as F^- . Interestingly, trifluoroacetate **13** accounted for only 8% of the

Scheme 5. The transient generation of $\text{C}(\text{sp}^2)\text{–F}$ bond strategy.

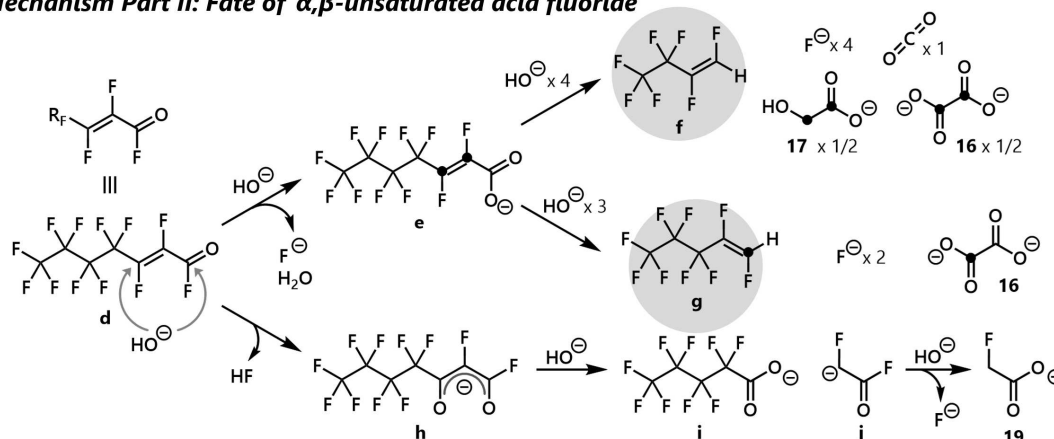
A. Houk and Dichtel (2022)



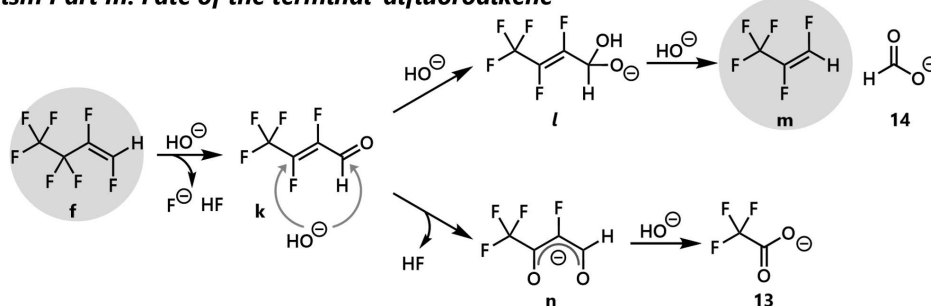
B. Mechanism Part I: Decarboxylation/ β -Elimination/Hydroxylation



C. Mechanism Part II: Fate of α,β -unsaturated acid fluoride



D. Mechanism Part III: Fate of the terminal difluoroalkene



Scheme 6. Defluorination of PFOA by Dichtel and Houk.

carbon-containing ions, indicating that the single-carbon shortening via decarboxylation was not the major path. Thus, the reaction mechanism was investigated experimentally and theoretically. First, the decarboxylation of the perfluoroalkyl carboxylate produced fluoroalkene intermediate **b** via β -fluorine elimination. The resulting fluoroalkene was prone to nucleophilic attack by hydroxide, affording the corresponding α,β -unsaturated carboxylic acid fluoride **d**. Then, two possible pathways were considered for the reaction between the highly electrophilic **d** and OH^- . The 1,2-addition route afforded carboxylate **e**. Then, **e** afforded fluoroalkenes via the triple-carbon shortening or double-carbon shortening, generating terminal difluoroalkene **f** or **g** along with glycolate **17**, oxalate **16**, and carbonate ions, which were experimentally observed. The 1,4-addition of hydroxide regenerated shorter perfluoroalkyl carboxylate **i**, which was used in the next decarboxylation

cycle. Fragmentation product fluoroacetate **19** was not detected because it was unstable under strong alkaline conditions at high temperatures. When the reaction of perfluoro-1*H*-heptane, the decarboxylation product of PFOA, was conducted at 40 °C, **19** was detected, revealing the operation of this path. Terminal difluoroalkene (e.g., **f**) was also electrophilic; hence, OH⁻ attacked the terminal carbon to afford α,β-unsaturated aldehyde **k**. Again, **k** can be attacked by OH⁻ via 1,2- or 1,4-addition. The 1,2-addition route afforded shorter fluoroalkene **l** with the release of formate **14**, while the 1,4-addition route afforded carboxylate. The reaction of **f** afforded **13**, while that of 1,2,3,3,3-pentafluoropropene (one carbon shorter than in **f**) afforded tartronate **18** via defluorination by hydroxide. From the viewpoint of the transient fluoroalkene strategy, the key feature of the reaction is that all chain-shortening reactions afforded fluoroalkenes, realizing continuous degradation.

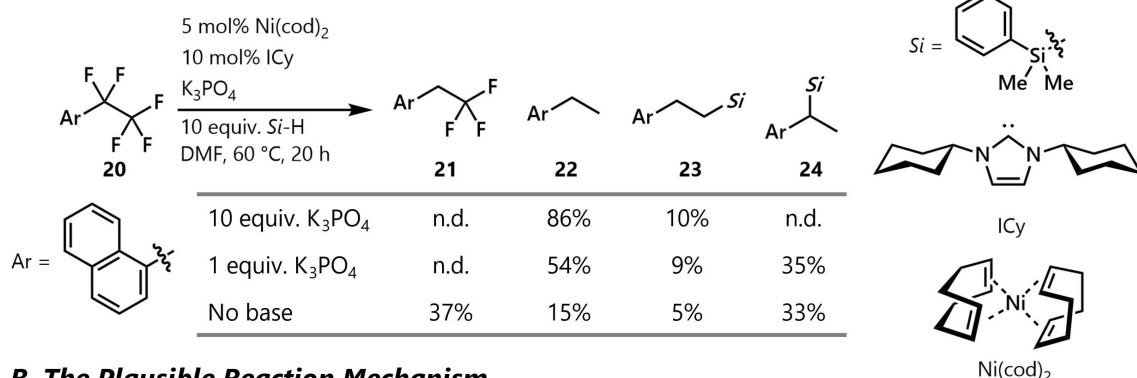
Doi, Ogoshi, and coworkers developed the exhaustive hydrodefluorination of perfluoroalkyl arenes with hydrosilane (Scheme 7).^[47] The reaction is the application of the related Ni-catalyzed hydrodefluorination of benzotrifluoride with hydrosilane to the longer perfluoroalkyl arenes.^[48] In the presence of Ni(cod)₂ and ICy as the catalyst precursors, the reaction of 1-(pentafluoroethyl)naphthalene (**20**) with dimethylphenylsilane proceeded in the presence of K₃PO₄. In the presence of 10 equiv. of K₃PO₄, exhaustive hydrodefluorination product **22** was obtained in 86% yield at 60 °C. As the byproduct, alkylsilane **23** was also formed. When the K₃PO₄ content was decreased to 1 equiv., the yield of **22** decreased, while alkylsilane **24** was observed, which was explained by the protonation of **24** with residual water in K₃PO₄. In the absence of the base, partial hydrodefluorination product **21** was observed, indicating that the base promoted the conversion of **21** to **22**. In fact, monitoring the reaction progress by periodical sampling supported that the hydrodefluorination of the benzylic group was the initial step. The deuterium incorporation trend with deuteriosilane was consistent with the scenario that the reaction proceeded via HF elimination, the hydrodefluorination of fluoroalkene **o**, the hydrosilylation of alkene **p**, and the protonation of the benzylic silane **q** (Scheme 7B). The key step was the generation of fluoroalkene **o** as the related reactions of the following steps (viz. the hydrodefluorination of the C(sp²)-F bond^[49] and hydrosilylation^[50]) were not surprising. The reason

for the facile elimination of HF with phosphate, a relatively weak base, was still unclear. The stoichiometric reaction of **21**, Ni(cod)₂, and ICy in the presence of K₃PO₄ afforded fluoroalkene complex **25** in 33% yield (Scheme 7C). Its structure was confirmed by X-ray crystallography. As the control experiment without a nickel source failed to afford fluoroalkene, the nickel complex would play a pivotal role in the generation of the alkene moiety. In this exhaustive hydrodefluorination, the generation of the fluoroalkene moiety would enable the subsequent hydrodefluorination of a longer perfluoroalkyl. In fact, although the yield was relatively low, the hydrodefluorination of 1-(heptafluoropropyl)naphthalene and 1-(nonafluorobutyl)naphthalene gave corresponding hydrocarbons. In these cases, the alkene moiety would facilitate the cleavage of the allylic C-F bond, rendering a continuous process. The lower yield of the hydrocarbon (< 10%) than those of the generated fluorosilanes (62% and 50%, respectively) would be attributed to the termination of the process by the hydrogenation or hydrosilylation of the C-C double bond.

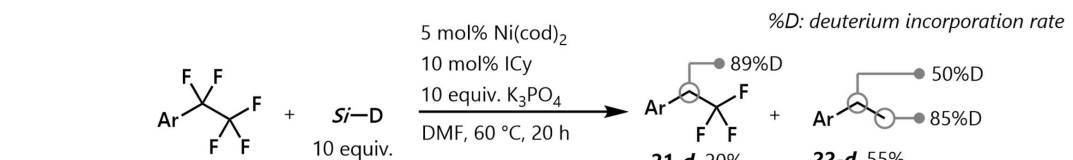
5. Summary and Outlook

The methodologies for the defluorination of longer perfluoroalkyl groups under mild conditions are briefly summarized, which are categorized into strong reduction, Lewis acid

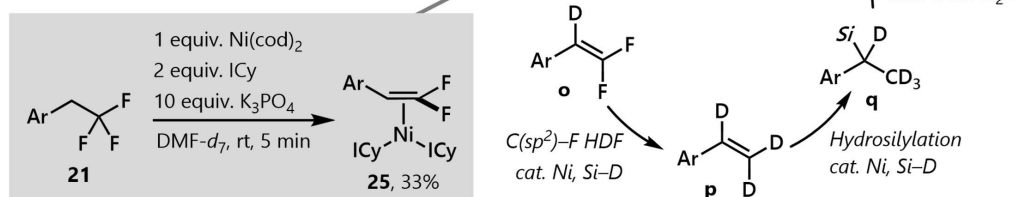
A. Doi and Ogoshi (2023)



B. The Plausible Reaction Mechanism



C. The Stoichiometric Reaction



Scheme 7. Exhaustive hydrodefluorination of perfluoroalkyl arenes.

activation, and the transient generation of fluoroalkene. The reduction chemistry has relatively rich examples. The recent example by Crimmin indicates that there is still considerable room for developing novel reduction reagents for perfluoroalkyl compounds. Lewis acid activation is also an interesting approach. Despite the intense research and development in this area, to the best of our knowledge, a successful example of a longer perfluoroalkyl group has not been reported since Ozerov's *Science* paper. The discovery of an effective Lewis acid that abstracts fluoride from the longer perfluoroalkyl group is awaited. The recent two examples of the transient fluoroalkene generation are described. This strategy could be the key technology for the mild decomposition of a longer perfluoroalkyl group. We hope that these strategies, as well as upcoming new ones, will contribute to the sustainability in organofluorine chemistry.

Acknowledgements

This work was supported by JST, PRESTO Grant Number JPMJPR2375, Japan.

Conflict of Interests

The authors declare no conflict of interest.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Keywords: Homogeneous catalysis · Lewis acids · C–F bond activation · Perfluoroalkyl substance · Hydrodefluorination

- [1] M. G. Evich, M. J. B. Davis, J. P. McCord, B. Acrey, J. A. Awkerman, D. R. U. Knappe, A. B. Lindstrom, T. F. Speth, C. Tebes-Stevens, M. J. Strynar, Z. Wang, E. J. Weber, W. M. Henderson, J. W. Washington, *Science* **2022**, 375, eabg9065.
- [2] A. R. Bock, B. E. Laird in *Perfluoroalkyl Substances* (Ed. B. Améduri), Royal Society of Chemistry, Croydon, **2022**, pp 1–21.
- [3] J. Glüge, M. Scheringer, I. T. Cousins, J. C. DeWitt, G. Goldenman, D. Herzke, R. Lohmann, C. A. Ng, X. Trier, Z. Wang, *Environ. Sci. Process. Impacts* **2020**, 22, 2345–2373.
- [4] D. O'Hagan, *Chem. Soc. Rev.* **2008**, 37, 308–319.
- [5] G. T. Ankley, P. Cureton, R. A. Hoke, M. Houde, A. Kumar, J. Kurias, R. Lanno, C. McCarthy, J. Newsted, C. J. Salice, B. E. Sample, M. S. Sepúlveda, J. Steevens, S. Valsecchi, *Environ. Toxicol. Chem.* **2021**, 40, 564–605.
- [6] X. Lei, Q. Lian, X. Zhang, T. K. Karsili, W. Holmes, Y. Chen, M. E. Zappi, D. D. Gang, *Environ. Pollut.* **2023**, 321, 121138.
- [7] L. J. Winchell, J. J. Ross, M. J. M. Wells, X. Fonoll, J. W. Norton, K. Y. Bell, *Water Environ. Res.* **2021**, 93, 826–843.
- [8] H. Hori, Y. Nagaoka, A. Yamamoto, T. Sano, N. Yamashita, S. Taniyasu, S. Kutsuna, I. Osaka, R. Arakawa, *Environ. Sci. Technol.* **2006**, 40, 1049–1054.
- [9] J. Li, B. R. Pinkard, S. Wang, I. V. Novosselov, *Chemosphere* **2022**, 307, 135888.
- [10] O. Soker, S. Hao, B. G. Trewyn, C. P. Higgins, T. J. Strathmann, *Environ. Sci. Technol. Lett.* **2023**, 10, 425–430.
- [11] S. Hao, Y. J. Choi, R. A. Deeb, T. J. Strathmann, C. P. Higgins, *Environ. Sci. Technol.* **2022**, 56, 6647–6657.
- [12] S. Hao, Y.-J. Choi, B. Wu, C. P. Higgins, R. Deeb, T. J. Strathmann, *Environ. Sci. Technol.* **2021**, 55, 3283–3295.
- [13] B. Wu, S. Hao, Y. Choi, C. P. Higgins, R. Deeb, T. J. Strathmann, *Environ. Sci. Technol. Lett.* **2019**, 6, 630–636.
- [14] J.-D. Hamel, J.-F. Paquin, *Chem. Commun.* **2018**, 54, 10224–10239.
- [15] H. Amii, K. Uneyama, *Chem. Rev.* **2009**, 109, 2119–2183.
- [16] T. A. Unzner, T. Magauer, *Tetrahedron Lett.* **2015**, 56, 877–883.
- [17] G. Yan, *Chem. Eur. J.* **2022**, 28, e202200231.
- [18] J.-M. A. Juve, J. A. Donoso Reece, M. S. Wong, Z. Wei, M. Ateia, *J. Hazard. Mater.* **2024**, 462, 132651.
- [19] D. M. Lemal, *J. Org. Chem.* **2004**, 69, 1–11.
- [20] D. D. MacNicol, C. D. Robertson, *Nature* **1988**, 332, 59–61.
- [21] J. A. Marsella, A. G. Gilicinski, A. M. Coughlin, G. P. Pez, *J. Org. Chem.* **1992**, 57, 2856–2860.
- [22] A. Paul, C. S. Wannere, H. F. Schaefer, *J. Phys. Chem. A* **2004**, 108, 9428–9434.
- [23] J. C. Rienstra-Kiracofe, G. S. Tschumper, H. F. Schaefer, S. Nandi, G. B. Ellison, *Chem. Rev.* **2002**, 102, 231–282.
- [24] J. Burdeniuc, B. Jedicka, R. H. Crabtree, *Chem. Ber.* **1997**, 130, 145–154.
- [25] J. L. Kiplinger, T. G. Richmond, C. E. Osterberg, *Chem. Rev.* **1994**, 94, 373–431.
- [26] K. Sung, R. J. Lagow, *J. Chem. Soc. Perkin Trans. 1* **1998**, 637–638.
- [27] L. Kavan, *Chem. Rev.* **1997**, 97, 3061–3082.
- [28] E. Nelson, T. J. Kilduff, A. A. Benderly, *Ind. Eng. Chem.* **1958**, 50, 329–330.
- [29] Y. Roina, A. Gonçalves, M. Fregnaux, F. Auber, G. Herlem, *ChemistrySelect* **2022**, 7, e202200153.
- [30] S. Tasker, R. D. Chambers, J. P. S. Badyal, *J. Phys. Chem.* **1994**, 98, 12442–12446.
- [31] J. Jansta, F. P. Dousek, J. Říha, *J. Appl. Polym. Sci.* **1975**, 19, 3201–3210.
- [32] J. Jansta, F. P. Dousek, *Electrochim. Acta* **1973**, 18, 673–674.
- [33] F. P. Dousek, J. Jansta, *Electrochim. Acta* **1975**, 20, 1–6.
- [34] J. Hlavatý, L. Kavan, *Carbon* **1999**, 37, 1029–1032.
- [35] N. Chakrabarti, J. Jacobus, *Macromolecules* **1988**, 21, 3011–3014.
- [36] D. J. Sheldon, J. M. Parr, M. R. Crimmin, *J. Am. Chem. Soc.* **2023**, 145, 10486–10490.
- [37] S. P. Green, C. Jones, A. Stasch, *Science* **2007**, 318, 1754–1757.
- [38] C. Jones, *Nat. Chem. Rev.* **2017**, 1, 0059.
- [39] J. C. L. Walker, H. F. T. Klare, M. Oestreich, *Nat. Chem. Rev.* **2019**, 4, 54–62.
- [40] H. F. T. Klare, M. Oestreich, *Dalton Trans.* **2010**, 39, 9176.
- [41] H. F. T. Klare, L. Albers, L. Süssse, S. Keess, T. Müller, M. Oestreich, *Chem. Rev.* **2021**, 121, 5889–5985.
- [42] M. Kira, T. Hino, H. Sakurai, *J. Am. Chem. Soc.* **1992**, 114, 6697–6700.
- [43] S. R. Bahr, P. Boudjouk, *J. Am. Chem. Soc.* **1993**, 115, 4514–4519.
- [44] V. J. Scott, R. Çelenligil-Çetin, O. V. Ozerov, *J. Am. Chem. Soc.* **2005**, 127, 2852–2853.
- [45] C. Douvris, O. V. Ozerov, *Science* **2008**, 321, 1188–1190.
- [46] B. Trang, Y. Li, X.-S. Xue, M. Ateia, K. N. Houk, W. R. Dichtel, *Science* **2022**, 377, 839–845.
- [47] R. Doi, M. Yasuda, N. Kajita, K. Koh, S. Ogoshi, *J. Am. Chem. Soc.* **2023**, 145, 11449–11456.
- [48] H. Iwamoto, H. Imiya, M. Ohashi, S. Ogoshi, *J. Am. Chem. Soc.* **2020**, 142, 19360–19367.
- [49] P. Fischer, K. Götz, A. Eichhorn, U. Radius, *Organometallics* **2012**, 31, 1374–1383.
- [50] A. S. Chang, K. E. Kawamura, H. S. Hennessy, V. M. Salpino, J. C. Greene, L. N. Zakharov, A. K. Cook, *ACS Catal.* **2022**, 12, 11002–11014.

Manuscript received: November 30, 2023

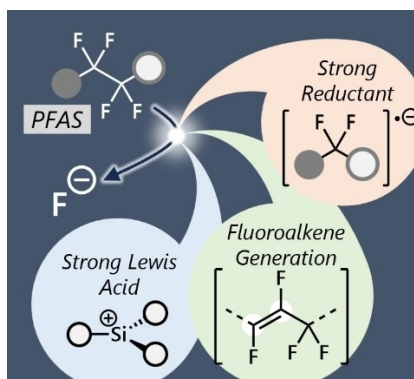
Revised manuscript received: January 18, 2024

Accepted manuscript online: January 21, 2024

Version of record online: ■■■■■

CONCEPT

Perfluoroalkyl substances (PFAS) are persistent environmental pollutants. In this work, we summarized recent progress on the chemical defluorination of PFAS via cleavage of unactivated C–F bonds in longer perfluoroalkyl groups under mild conditions ($\sim 150^\circ\text{C}$). In addition to classic reductive defluorination, the strategies featuring Lewis acidic activation and transient generation of an unsaturated bond are described.



Dr. R. Doi*, Prof. S. Ogoshi*

1 – 8

Chemical Strategies for the Cleavage of the C(sp³)–F Bonds in Perfluoroalkyl Groups