Available online at www.sciencedirect.com
ScienceDirect
Journal of Fluorine Chemistry 127 (2006) 1302–1310
JOURNAL OF FLUORINE CHEMISTRY
www.elsevier.com/locate/fluor

A convenient and efficient method for incorporation of pentafluorosulfanyl (SF_5) substituents into aliphatic compounds

William R. Dolbier Jr.[a,*], Samia Aït-Mohand[a], Tyler D. Schertz[a], Tatiana A. Sergeeva[a], Joseph A. Cradlebaugh[a], Akira Mitani[a], Gary L. Gard[b], Rolf W. Winter[b], Joseph S. Thrasher[c]

[a] *Department of Chemistry, P.O. Box 117200, University of Florida, Gainesville, FL 32611-7200, United States*
[b] *Department of Chemistry, Portland State University, Portland, OR 97207-0751, United States*
[c] *Department of Chemistry, The University of Alabama, P.O. Box 870336, Tuscaloosa, AL 35487-0336, United States*

Received 10 March 2006; received in revised form 27 April 2006; accepted 1 May 2006
Available online 7 May 2006

Dedicated to Prof. Boris Zemva on the occasion of his receiving the 2006 ACS Award for Creative work in Fluorine Chemistry.

Abstract

Both SF_5Cl and SF_5Br undergo smooth, high yield addition to alkenes and alkynes under the mild free radical chain reaction conditions of triethylborane initiation at low temperature, although the SF_5Br chemistry is somewhat limited by its competing high electrophilic reactivity with electron rich alkenes. The SF_5Cl addition reaction is relatively insensitive to a wide variety of non-allylic functionalities.

Keywords: Pentafluorosulfanyl substituent; Free radical chain reaction; SF_5Cl; SF_5Br; Triethylborane initiation

1. Introduction

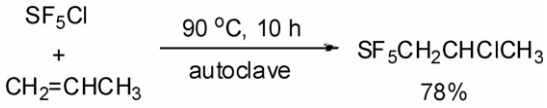
Because of the profound influence that incorporation of fluorine-containing substituents can have upon the physical and chemical properties, and biological activity of molecules, there is currently great interest in new methodology for the preparation of selectively fluorinated organic compounds. Thus, for example, methods for putting the bulky, highly electronegative and generally inert trifluoromethyl group into organic compounds have received much research attention during recent years. Another fluorinated substituent that is beginning to attract the attention of synthetic organic chemists is the pentafluorosulfanyl (SF_5) group [1–4], which bears much similarity to the trifluoromethyl group, but is more electronegative ($\sigma_p = +0.68$ versus +0.54 for CF_3) [5], and more sterically demanding. The SF_5 substituent should emulate the CF_3 group in altering molecular properties such as density, refractive index, dipole moment, lipophilicity, thermal and chemical stability, and it should have a similar but intriguingly distinct impact on biological activity, as foreshadowed by its demonstrated effect on insecticidal properties [6,7].

However, until recently the methods required to put an SF_5 substituent onto a benzene ring (elemental F_2 or oxidative fluorination by AgF_2) [8–11] or to incorporate an SF_5 group into aliphatic compounds (high pressure autoclave or specialized photochemical procedures) [12–15] did not encourage utility by synthetic organic chemists. Recently, we reported, in communication form, a new and convenient alkene addition procedure that allowed the synthesis of both SF_5 substituted aliphatic [16] and aromatic compounds [17]. In the present paper, we present additional data that serve to demonstrate the scope and limitations of the new aliphatic chemistry.

SF_5Cl is presently the only commercially available "reagent" that can be used to introduce the SF_5 substituent into aliphatic compounds. As a gaseous pseudo-halogen, this reagent cannot be used as an electrophilic source of SF_5, but ever since Roberts' pioneering work in 1961 [12], it has been used in free radical chain alkene/alkyne addition processes [18], generally done thermally, in an autoclave, with or without an initiator, or using room temperature gas phase or low

* Corresponding author. Tel.: +1 352 392 0591; fax: +1 352 846 1962.
E-mail address: wrd@chem.ufl.edu (W.R. Dolbier Jr.).

0022-1139/$ – see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.jfluchem.2006.05.003



Scheme 1.

temperature solution phase photochemical processes. For example (Scheme 1) [12].

Although less accessible, SF_5Br also has potential as a source of SF_5 substituents in aliphatic systems. Gard explored thermal and photochemical approaches for additions of SF_5Br to a limited group of alkenes [14,19–23], and Lal and Minnich of Air Products, Inc., recently delineated the limited scope of such additions to alkenes and alkynes, when using classic thermal methodology [24]. We have now been able to assess and compare the usefulness of SF_5Br versus SF_5Cl when using our new Et_3B-initiated process, and these results are also presented in this paper.

2. Results and discussion

In order for SF_5-derivatives to become incorporated into the day-to-day strategic planning of working synthetic organic chemists, it was necessary that a convenient, bench-top procedure be developed for introduction of SF_5 substituents into organic substrates. We believe that the method of using low temperatures and Et_3B initiation constitutes such a process. The method is based upon our discovery that Et_3B, apparently uniquely, initiates the free radical chain addition of SF_5Cl to unsaturated compounds at the low temperatures required for convenient use of SF_5Cl in solution at atmospheric pressure. Triethylborane has been recognized for more than a decade to be a unique low temperature initiator of free radical reactions [25]. Although other potential initiators have been examined, thus far Et_3B remains the only one that has successfully initiated the SF_5Cl addition reactions at such low temperatures.

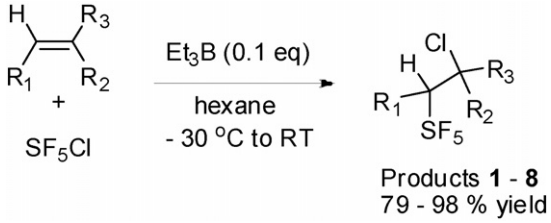
2.1. SF_5Cl additions to alkenes

With a boiling point of −21 °C, SF_5Cl is readily condensed into hexane, which contains the alkene or alkyne substrate, at −40 °C. When the Et_3B initiator is added by syringe at ∼−30 °C, an immediate reaction is evident, and, for most substrates, the reaction is effectively complete after 30 min. The reaction can be worked up by simple evaporation of the hexane to give, in most cases, essentially pure product. (No significant impurities are observed by ^1H, ^{19}F, or ^{13}C NMR, but passage through a short column is recommended before further use, to eliminate possible traces of Et_3B and its oxidation products.) Table 1 gives the yields for addition of SF_5Cl to a broad variety of alkenes (Scheme 2).

Table 1
Yields for addition of SF_5Cl to alkenes[a]

R_1	R_2	R_3	Product (% yield)	Reference
H	n-C_6H_{13}	H	**1**, 95	[16]
H	n-C_4H_9	H	**2**, 98	[16,26]
H	t-C_4H_9	H	**3**, 96	[16]
H	C_2H_5	C_2H_5	**4**, 89	[16]
n-C_3H_7	H	n-C_3H_7	**5**, 95[b]	[16]
$(CH_2)_4$	$(CH_2)_4$	H	**6**, 98[b]	[12,16]
H	p-tolyl	H	**7**, 79	[16]

[a] In hexane, at −30 °C, 0.1 equiv. Et_3B, 30 min.
[b] One major diastereomer (>90% by NMR).

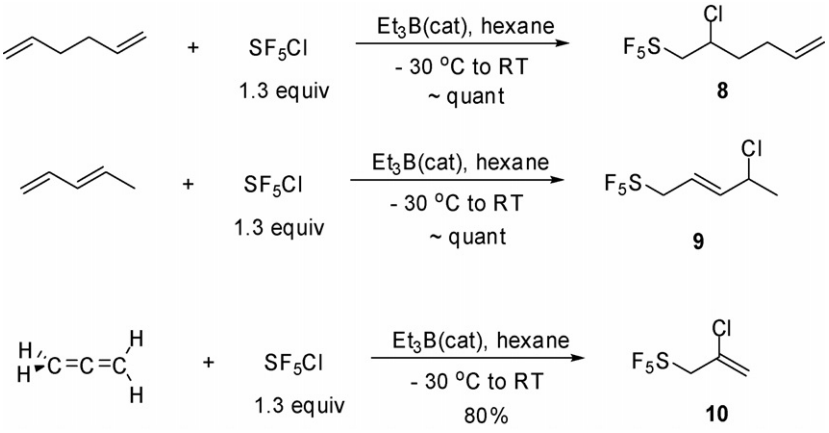


Scheme 2.

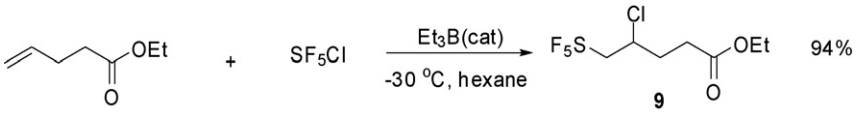
Reactions with dienes, non-conjugated, conjugated or cumulated all proceeded normally (using 1.3 equiv. SF_5Cl) to give high yields of 1:1 adducts. Thus 1,5-hexadiene, 1,3-pentadiene, and allene gave adducts **8**, **9**, in almost quantitative yield and **10** in 80% yield, respectively (Scheme 3).

Compound **10** had been obtained earlier by Seppelt in 44% yield, using the usual thermal, high pressure autoclave conditions [13].

The reaction proved to be quite insensitive to functional groups that were not conjugated with the double bond. Thus



Scheme 3.



Scheme 4.

reaction of alkenyl halides, esters, ketones all led to high yields of adducts, i.e. Schemes 4 and 5 (Table 2).

Although it was possible to carry out the addition of SF_5Cl to a conjugated hydrocarbon system such as *p*-methylstyrene, additions to α, β-unsaturated carbonyl compounds, such as ethyl acrylate or ethyl methacrylate, were *not* successful, presumably because of a combination of reduced chain transfer rate to the electrophilic propagating radical, and the problem of the ester tying up the Et_3B initiator [28], thus inhibiting free radical initiation and allowing polymerizing chain propagation to dominate the reaction.

2.2. SF_5Cl additions to alkynes

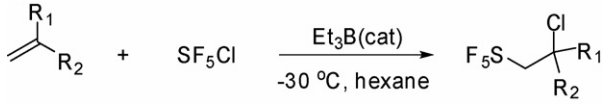
Alkynes also proved to be excellent substrates for addition of SF_5Cl under these low temperature, Et_3B-initiated conditions. Table 3 (Scheme 6) gives the results for addition to three typical alkynes.

In the reaction with phenyl acetylene, a 2:1 adduct, **23**, was also obtained in 27% yield (Scheme 7). In this case, addition of the propagating radical intermediate to a second phenyl acetylene is obviously competing with the chain transfer step. Using a larger excess of SF_5Cl in the reaction can minimize this 2:1 product.

2.3. Results using SF_5Br

SF_5Br has been reported to be generally unproductive in addition of SF_5 and Br across the double bond of simple aliphatic alkenes, such as 1-hexene (Scheme 8) [26].

Apparently, instead of undergoing the desired free radical chain addition reaction with hydrocarbon alkenes, SF_5Br prefers

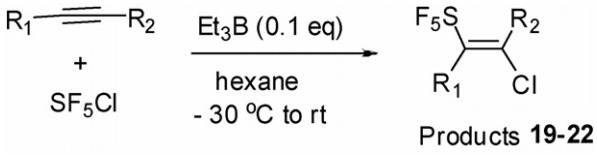


Scheme 5.

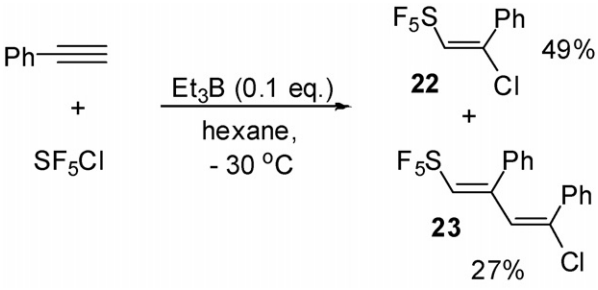
Table 3
Addition of SF_5Cl to Alkynes[a]

R_1	R_2	Product[b], yields
n-C_3H_7	*n*-C_3H_7	**19**, 93%
H	*n*-C_4H_9	**20**, 90%
H	*n*-C_6H_{13}	**21**, 94%
H	Ph	**22**, 49% + **23**, 27%

[a] In hexane, at −30 °C, 0.1 equiv. Et_3B, 30 min.
[b] Single diastereomer in each case.



Scheme 6.



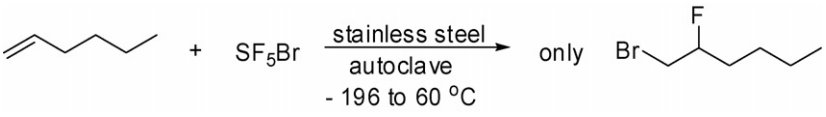
Scheme 7.

to react in an electrophilic manner via attack by the double bond at Br to form the bromonium ion plus SF_5^-, which provides fluoride ion to complete the addition of BrF to the alkene.

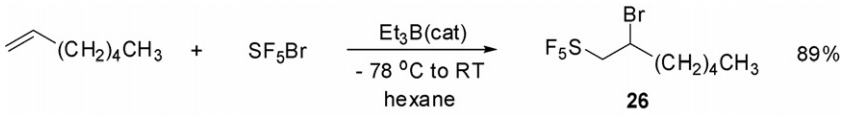
Lal and Minnich found that such electrophilic chemistry could be averted in the case of terminal alkenes by carrying out the reaction in a FEP reactor (dilute pentane solution, −30 °C), under which conditions they obtained from 1-hexene the $SF_5CH_2CHBr(CH_2)_3CH_3$ product in excellent yield (93%) [24].

Table 2
Addition of SF_5Cl to functionalized alkenes

Alkene substrate	R_1	R_2	1,2-Adduct	Yield (%)	Reference
CH_2=CHOAc	H	OAc	**11**	98	[14,27]
CH_2=$CHCH_2CH_2CO_2Et$	H	$(CH_2)_2CO_2Et$	**12**	94	
CH_2=$CHCH_2CH_2COCH_3$	H	$(CH_2)_2COCH_3$	**13**	93	
CH_2=$CH(CH_2)_7CH_2OH$	H	$(CH_2)_8OH$	**14**	73	[26]
CH_2=$CH(CH_2)_7CH_2OAc$	H	$(CH_2)_8OAc$	**15**	94	[26]
CH_2=$CH(CH_2)_7CH_2Br$	H	$(CH_2)_8Br$	**16**	89	
CH_2=$CHCH_2CO_2Et$	H	CH_2CO_2Et	**17**	70	
CH_2=$C(CH_3)OAc$	CH_3	OAc	**18**	94	



Scheme 8.



Scheme 9.

Under our conditions of Et_3B initiation, it was found that additions of SF_5Br to terminal alkenes could be carried out quite efficiently in normal glass apparatus. The reactions were carried out in hexane by mixing all of the ingredients at −78 °C, adding initiator, and then allowing the reaction mixture to warm slowly to room temperature (Scheme 9). Yields of adducts (**24**–**27**) from ethylene, 1-hexene, 1-heptene, and 1-octene were 84, 73, 89, and 99%, respectively. The reaction with ethylene was carried out in F-142b (CH_3CF_2Cl, bp = −9 °C) as solvent in order to facilitate isolation of product. In this case, because of the volatility of the ingredients, one must add the initiator very carefully in order to avoid loss of these ingredients due to an excessive exotherm. Previously, the ethylene adduct, $SF_5CH_2CH_2Br$ (**24**), had been reported as being formed quantitatively by the uninitiated reaction of SF_5Br with ethylene in a glass vessel (no solvent) at room temperature for 10 h [29].

A low yield (30%) of adduct (**28**) could be obtained in the reaction with cyclohexene, but unfortunately, other reactions with non-terminal hydrocarbon alkenes, specifically *trans*-2-octene, 2-methyl-2-butene, and cyclopentene gave no more than traces of products that contained the SF_5 substituent. When an addition reaction with SF_5Br is successful, the reaction mixture remains clear and colorless, as are the reactions with SF_5Cl. However, when the reaction goes awry, as with a non-terminal alkene, the reaction darkens quickly, which seems to be an indication that an ionic reaction is taking place, instigated by a formal donation of Br^+, rather than the desired free radical chain reaction. Thus the greater the nucleophilic character of an alkene, the more likely it will be that SF_5Br will react via Br^+ donation.

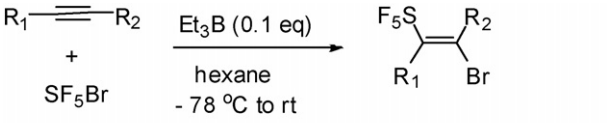
Thus SF_5Br should be particularly appropriate for use with *electron deficient* alkenes. Indeed, Gard has reported the useful addition of SF_5Br to acrylates, allylic esters, and fluorinated alkenes using standard thermal and/or photochemical (sun-lamp) conditions [14,20–23]. Unfortunately, however, the use of our low temperature, Et_3B-initiated procedure led to no significant amount of addition products for these electron deficient substrates, nor for addition to α-methystyrene. Moreover, heavily fluorinated alkenes, such as perfluoropropene or perfluoro allyl chloride also were unreactive under our reaction conditions.

More versatile in its additions to alkynes, SF_5Br was earlier found to add effectively to propyne, 3,3,3-trifluoropropyne, propargylic esters and acetylene itself [30–32]. Under our low temperature, Et_3B-initiated conditions it gave excellent yields of adducts with terminal and internal, alkyl or aryl substituted alkynes. Note that the reaction with phenylacetylene leads only to 1:1 adduct, with no 2:1 adduct being formed as was the case for the reaction with SF_5Cl (Scheme 10).

2.4. Summary of addition results

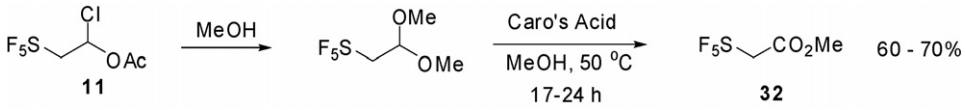
SF_5Cl turns out to be much superior to SF_5Br as a reagent for free radical addition to a broad variety of alkenes, when using virtually any procedure, but certainly when using our Et_3B-initiated process. Although SF_5Br behaves better in its reactions with alkynes, the full scope of such additions has not yet been probed adequately for firm conclusions to be made. Since SF_5Cl adds well to both alkene and alkyne substrates and it is currently more readily available than SF_5Br, it may be considered the preferred reagent for incorporation of SF_5 substitutents into aliphatic systems.

All of the addition reactions of SF_5Cl are regiospecific and highly diastereoselective, with essentially one product being formed from the additions to cyclohexene, *trans*-4-octene and the alkynes. Although the specific stereochemistries of products **5**, **6**, **19**–**22** have not been confirmed, one can be almost certain that the stereochemical outcomes of these reactions are sterically controlled, and that the alkyne and cyclohexene products are *E*-isomers, and that the product (**5**) from *trans*-4-octene is *erythro*. All of the alkyne adducts were novel when reported in the communication, although the SF_5Cl adduct of propyne had been previously reported [12]. Although many of the alkene adducts had been previously reported [12,26], styrenes, 2,2-disubstituted alkenes, and non-terminal alkenes had not heretofore been effective substrates for SF_5Cl addition. The mildness of the Et_3B-catalyzed reaction conditions obviously contributes to the apparent broad applicability of this procedure.

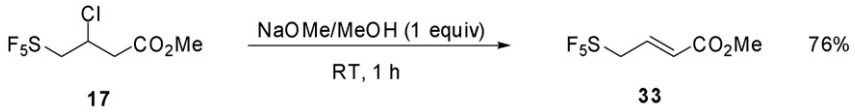


29, $R_1 = R_2 = n\text{-}C_3H_7$ (99%)
30, $R_1 = H$, $R_2 = CH_2OAc$ (67%)
31, $R_1 = H$, $R_2 = Ph$ (79%)

Scheme 10.



Scheme 11.



Scheme 12.

2.5. Some chemistry of the SF_5Cl adducts

In an effort to develop useful SF_5-containing synthetic "building blocks", some of the alkene and alkyne adducts discussed above were subjected to further investigation.

Gard had shown that the SF_5Cl adduct with vinyl acetate (**11**) could be converted to the α-SF_5 substituted ester, $SF_5CH_2CO_2Me$ (**32**) [14]. Because of the large electronegativity of the SF_5 group, we were interested in the potential of that compound to behave like a malonic ester analog in facilitating alkylations. In the course of our studies, a different overall procedure was developed for synthesis of ester **32** (Scheme 11). Unfortunately, no conditions could be identified that would allow ester **32** to undergo alkylation. Bases such as KO-*t*-Bu, NaH, and LDA all failed to facilitate alkylation by reactive halides, such as methyl iodide and allyl iodide. When a solution of **32** was treated with LDA at −78 °C, a bright yellow solution ensued, presumably indicating the formation of the enolate, but when methyl iodide was added none of the expected product could be detected. As the solution warmed to room temperature, the yellow color disappeared, and no SF_5-containing products could be observed by ^{19}F NMR upon work up of the reaction.

Evidence that the enolate was indeed being formed was obtained by treatment of **30** with methoxide base in CH_3OD as solvent, where upon deuterium exchange of the substrate was observed to occur, as indicated by NMR and mass spectral analysis.

Thinking that the lack of nucleophilic behavior by the enolate of ester **32** might derive from a simple steric influence of the proximate SF_5 substituent, its vinylogous analog, **33**, was synthesized from ester **17**. Ester **33** has recently been prepared by an alternate route by Brel and its dienophilic behavior examined (Scheme 12) [33]. The enolate of this ester has two potential nucleophilic sites, one of which should not be hindered by the SF_5 substituent. Nevertheless, this ester also could not be alkylated under various base-catalyzed conditions. Therefore, one must conclude that when the SF_5 substituent stabilizes a carbanion in a "conjugative" sense, such stabilization must seriously diminish the nucleophilicity of the carbanion.

In one other reaction of SF_5Cl alkene adducts hydrolysis of adduct **18** led to ketone **34** (Scheme 13) [34].

Because we were interested in determining the potential for cycloaddition reactions of SF_5 substituted alkynes, conditions for clean elimination of HCl from alkyne adduct **20** were identified. The cycloaddition studies of the resulting alkynes will be reported subsequently (Scheme 14).

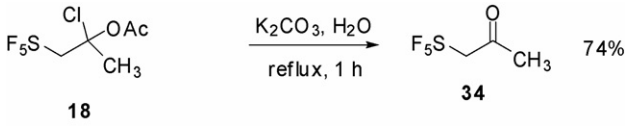
3. Experimental

3.1. General

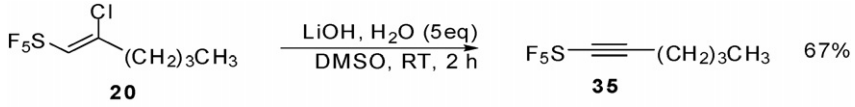
All NMR spectra are in $CDCl_3$ using TMS as internal standard for ^1H (300 MHz) and ^{13}C NMR (75.46 MHz), and $CFCl_3$ as internal standard for ^{19}F NMR spectra (282 MHz). The SF_5 group always appears as an AB_4 system in its ^{19}F NMR spectra.

3.2. Typical procedure for addition of SF_5Cl or SF_5Br to alkenes and alkynes [35]

Into a three-necked flask equipped with a dry ice reflux condenser and a nitrogen inlet were added at −40 °C, 15 mL of anhydrous hexane, alkene or alkyne (3–4 mmol) and SF_5Cl or SF_5Br (1.2 equiv.). The solution was stirred at this temperature for 5 min and then Et_3B (0.1 equiv., 1 M in hexane) was added slowly using a syringe. The solution was vigorously stirred for 1 h at −30 to −20 °C, and then the mixture was warmed to room temperature. The mixture was hydrolyzed with aqueous $NaHCO_3$ (10%) and the organic layer dried over $MgSO_4$. The solvent was removed and the crude product was passed through a short column of silica gel, eluting with CH_2Cl_2. Removal of



Scheme 13.



Scheme 14.

solvent in most cases provided the products in essentially pure form without the need for additional purification.

*3.2.1. 2-Chloro-1-pentafluorosulfanyloctane (**1**) [16]*

^{1}H NMR, δ 0.90 (m, 3H), 1.35 (br s, 6H), 1.45 (m, 1H), 1.56 (m, 1H), 1.75 (m, 1H), 1.90 (m, 1H), 3.95 (m, 2H, CH_2SF_5), 4.35 (m, 1H, CHCl); ^{19}F NMR, δ_A 82.9 (p, 1F), δ_B 65.7 (d, J_{AB} = 146 Hz, 4F); ^{13}C NMR, δ 14.2, 22.8, 26.2, 28.7, 31.8, 37.7, 56.1 (p, J = 4.5 Hz), 77.2 (p, J = 12.1 Hz).

*3.2.2. 2-Chloro-1-pentafluorosulfanylhexane (**2**) [16,26]*

^{1}H NMR, δ 0.86 (t, J = 7 Hz, 3H), 1.2–1.5 (m, 4H), 1.68 (m, 1H), 1.85 (m, 1H), 3.87 (m, 2H, CH_2SF_5), 4.27 (m, 1H, CHCl); ^{19}F NMR, δ_A 82.9 (p, 1F), δ_B 65.7 (d, J_{AB} = 143 Hz, 4F); ^{13}C NMR, δ 14.0, 22.1, 28.3, 37.4, 56.5 (p, J = 5.1 Hz), 77.5 (p, J = 13.1 Hz).

*3.2.3. 2-Chloro-3,3-dimethyl-1-pentafluorosulfanylbutane (**3**) [16]*

^{1}H NMR, δ 0.99 (s, 9H), 3.88 (m, 2H, CH_2SF_5), 4.11 (m, 1H, CHCl); ^{19}F NMR, δ_A 83.9 (p, 1F), δ_B 65.4 (d, J_{AB} = 148 Hz, 4F); ^{13}C NMR, δ 26.5, 37.2, 65.8 (p, J = 4.1 Hz), 76.0 (p, 13.9 Hz).

*3.2.4. 2-Chloro-2-ethyl-1-pentafluorosulfanylbutane (**4**) [16]*

^{1}H NMR, δ 1.10 (t, J = 7.3 Hz, 6H), 2.02 (q, J = 7.3 Hz, 4H), 4.02 (pd, J = 8.8 and 2.9 Hz, 2H, CH_2SF_5); ^{19}F NMR, δ_A 83.9 (p, 1F), δ_B 69.6 (d, J_{AB} = 147 Hz, 4f); ^{13}C NMR, δ 8.7, 33.5, 75.9 (m), 76.9(m).

*3.2.5. 4-Chloro-3-pentafluorosulfanylhexane (**5**) [16]*

^{1}H NMR, δ 0.96 (m, 6H), 1.4–2.2 (overlapping m, 8H), 4.18 (m, 1H, $CHSF_5$), 4.51 (br d, J = 10.2 Hz, 1H, CHCl); ^{19}F NMR, δ_A 85.8 (p, 1F), δ_B 59.5 (d, J_{AB} = 144 Hz, 4F); ^{13}C, δ 13.4, 14.0, 20.5, 21.6, 31.0, 36.0, 60.9 (m, J = 4.9 Hz), 92.4 (m, J = 16.7 Hz).

*3.2.6. 1-Chloro-2-pentafluorosulfanylcyclohexane (**6**) [12,16]*

^{1}H NMR, δ 1.4–2.2 (overlapping m, 8H), 4.04 (m, 1H, $CHSF_5$), 4.49 (m, 1H, CHCl); ^{19}F NMR, δ_A 85.2 (p, 1F), δ_B 57.2 (d, J_{AB} = 141 Hz, 4F); ^{13}C NMR, δ 21.4, 23.1, 27.0, 34.0, 57.0 (p, J = 3.5 Hz), 88.6 (m, J = 8.0 Hz).

*3.2.7. 1-Chloro-1-(4-methylphenyl)-2-pentafluorosulfanylethane (**7**) [16]*

^{1}H NMR, δ 2.25 (s, 3H), 4.18 (m, 2H, CH_2SF_5), 5.24 (t, J = 6.6 Hz, 1H, CHCl) 7.10 and 7.18 (AB, J_{AB} = 8.1 Hz, 4H); ^{19}F NMR, δ_A 82.2 (p, 1F), δ_B 66.1 (d, J_{AB} = 145 Hz, 4F); ^{13}C NMR, δ 21.4, 56.5 (m, J = 5 Hz), 77.5 (m, J = 13.0 Hz), 127.0, 130.0, 135.7, 139.6.

*3.2.8. 5-Chloro-6-pentafluorosulfanylhex-1-ene (**8**)*

^{1}H NMR, δ 5.75 (m, 1H), 5.11 (m, 2H), 4.39 (m, 1H), 3.95 (m, 2H), 2.5–1.7 (m, 4H); ^{19}F NMR, δ 82.77 (p, 1F), 65.91 (d, 4F).

*3.2.9. 4-Chloro-1-pentafluorosulfanylpent-2-ene (**9**)*

^{1}H NMR, δ 5.93 (m, 2H), 4.55 (m, 1H), 4.27 (m, 2H), 1.63 (m, 3H); ^{19}F NMR, δ 85.3 (q, 1F), 57.1 (d, 4F).

*3.2.10. 2-Chloro-3-pentafluorosulfanylprop-1-ene (**10**) [13]*

^{1}H NMR, δ 5.69 (m, 1H), 5.65 (m, 1H), 4.40 (q, J = 5.5 Hz, 2H); ^{19}F NMR, δ 79.8 (q, 1F), 65.0 (d, 4F).

*3.2.11. 1-Chloro-2-pentafluorosulfanylethyl acetate (**11**) [14]*

^{1}H NMR, δ 2.10 (s, 3H), 4.10 (m, 1H), 4.24 (m, 1H, $CHSF_5$), 6.89 (dm, J = 10 Hz, 1H, CHCl); ^{19}F NMR, δ_A 80.3 (p, 1F), δ_B 66.0 (d, J_{AB} = 147 Hz, 4F); ^{13}C NMR, δ 20.7, 73.6 (m, J = 14.6 Hz), 77.0 (m, J = 5.5 Hz), 167.8.

*3.2.12. Ethyl 4-chloro-5-pentafluorosulfanylpentanoate (**12**)*

^{1}H NMR, δ 4.39 (m, J = 3.3 Hz, 1H), 4.09 (q, J = 7.1 Hz, 2H), 3.90 (m, J = 6.4 Hz, 1H), 2.50 (m, 2H), 2.29 (m, 1H), 1.90 (m, 1H), 1.20 (t, J = 7.1 Hz, 3H); ^{19}F NMR, δ_A 82.4 (q, 1F), δ_B 66.1 (d, J_{AB} = 147 Hz, 4F); ^{13}C NMR, δ 14.75, 31.31, 33.17, 55.57 (m), 61.46, 77.23 (m), 172.71.

*3.2.13. 5-Chloro-6-pentafluorosulfanylhexan-2-one (**13**)*

^{1}H NMR, δ 4.42 (m, 1H), 3.96 (m, 2H), 2.73 (t, J = 7.8 Hz, 2H), 2.31 (m, 1H), 2.19 (s, 3H), 1.88 (m, 1H); ^{19}F NMR, δ_A 82.4 (p, 1F), 65.9 (d, J_{AB} = 146 Hz, 4F); ^{13}C NMR, δ 30.34, 31.60, 39.99, 55.63 (m), 77.23 (m), 207.11; Anal. Calcd for $C_6H_{10}OSF_5$: C, 27.65; H, 3.87. Found: C, 27.32; H, 3.70.

*3.2.14. 9-Chloro-10-pentafluorosulfanyldecan-1-ol (**14**) [26]*

^{1}H NMR, 4.30 (m,1H), 3.93 (m, 4H), 3.36 (t, J = 6 Hz, OH), 1.2–2.0 (m, 14H); ^{19}F NMR, δ_A 88.9 (p, 1F), δ_B 65.7 (d, J_{AB} = 147 Hz, 4F); ^{13}C NMR, δ 26.08, 26.10, 28.80, 28,86, 29.36, 29.64, 29.91, 55.95 (m), 62.37, 77.10 (m).

*3.2.15. 9-Chloro-10-pentafluorosulfanyldecyl acetate (**15**) [26]*

^{1}H NMR, δ 4.24 (m, 1H), 3.94 (t, J = 8 Hz, 2H), 3.86 (m, 2H), 1.92 (s, 3H), 1.80 (m, 1H), 1.65 (m, 1H), 1.16–1.58 (m, 12H); ^{19}F NMR, δ_A 82.76 (p, 1F), δ_B 65.45 (d, J_{AB} = 147 Hz, 4F); ^{13}C NMR, δ 26.12, 26.20, 28.86, 28.94, 29.36, 29.50, 31.89, 37.72, 56.11 (m), 64.72, 77.24 (m), 171.0.

*3.2.16. 1-Bromo-9-chloro-10-pentafluorosulfanyldecane (**16**)*

^{1}H NMR, δ 4.34 (m, 1H), 3.96 (m, 2H), 3.39 (t, J = 7 Hz, 2H), 1.90–1.20 (m, 14H); ^{19}F NMR, δ_A 82.85 (p, 1F), δ_B 65.70 (d, J_{AB} = 146 Hz, 4F); ^{13}C NMR, δ 28.40, 28.91, 28.96, 29.48, 31.92, 33.08, 34.21, 37.77, 56.12 (m), 77.23 (m).

*3.2.17. Methyl 3-chloro-4-pentafluorosulfanylbutanoate (**17**)*

^{1}H NMR, δ 4.75 (m, 1H), 4.08 (m, 2H), 4.34 (s, 3H), 3.0 (dd, J = 16.6, 5.5 Hz, 1H), 2.85 (dd, J = 16.3, 7.7 Hz, 1H); ^{19}F

NMR, δ_A 79.59 (p, 1F), δ_B 63.5 (d, J_{AB} = 147 Hz, 4F); ^{13}C NMR, δ 42.0, 50.5, 52.59 (m), 77.46 (m), 169.5.

*3.2.18. 2-Chloro-1-pentafluorosulfanylprop-2-yl acetate (**18**)*

^{1}H NMR, δ 4.95 (dp, J = 14.5, 8.5 Hz, 1H), 4.03 (dp, J = 14.5, 8.0 Hz, 1H), 2.20 (s, 3H), 2.12 (s, 3H); ^{19}F NMR, δ_A 77.8 (p, 1F), δ_B 64.68 (d, J_{AB} = 144 Hz, 4F).

*3.2.19. (E)-5-Chloro-4-pentafluorosulfanyloct-4-ene (**19**)*

^{1}H NMR, δ 0.96 (m, 6H), 1.64 (m, 4H), 2.57 (m, 2H), 2.70 (m, 2H); ^{19}F NMR, δ_A 86.5 (p, 1F), δ_B 64.1 (d, J_{AB} = 149 Hz, 4F); ^{13}C NMR, δ 13.5,14.3, 21.2, 35.9, 40.3, 146.2 (p, J = 4 Hz), 153.2 (m, J = 14 Hz).

*3.2.20. (E)-2-Chloro-1-pentafluorosulfanyloct-1-ene (**20**)*

^{1}H NMR, δ 0.89 (t, J = 6 Hz, 3H), 1.31 (br m, 6H), 1.62 (m, 2H), 2.66 (t, J = 7.6 Hz, 2H), 6.59 (p, J = 8.3 Hz, 1H); ^{19}F NMR, δ_A 82.6 (p, 1F), δ_B 66.9 (d, J_{AB} = 143 Hz, 4F); ^{13}C NMR, δ 14.2, 22.7, 27.4, 28.8, 31.6, 36.1, 137.0 (m, J = 21 Hz), 148.1 (m, J = 6.5 Hz).

*3.2.21. (E)-2-Chloro-1-pentafluorosulfanylhex-1-ene (**21**)*

^{1}H NMR, δ 0.95 (t, J = 8 Hz, 3H), 1.39 (m, 2H), 1.62 (m, 2H), 2.68 (t, J = 7.5 Hz, 2H), 6.60 (p, J = 8.4 Hz, 1H); ^{19}F NMR, δ_A 82.5 (p, 1F), δ_B 66.9 (d, J_{AB} = 150 Hz, 4F).

*3.2.22. (E)-1-Chloro-2-pentafluorosulfanyl-1-phenylethene (**22**)*

^{1}H NMR, δ 6.97 (p, J = 7.8 Hz, 1H), 7.43 (m, 5H); ^{19}F NMR, δ_A 80.9 (p, J = 152 Hz, 1F), δ_B 68.9 (d, J_{AB} = 152 Hz, 4F); ^{13}C NMR, δ 127.9, 128.6, 130.2, 132.0, 135.9, 138.2 (m), 143.2 (m); HRMS: Calcd for $C_8H_6ClSF_5$: 263.9799. Found: 263.9786.

*3.2.23. (1E,3Z)-1-Chloro-1,3-diphenyl-4-pentafluorosulfanylbuta-1,3-diene (**23**)*

^{1}H NMR, δ 6.25 (p, J = 8.6 Hz, 1H), 6.52 (br s, 1H), 7.18 (m, 2H), 7.28 (m, 2H), 7.32 (m, 6H); ^{19}F NMR, δ_A 83.1 (p, 1F), δ_B 68.1 (d, J_{AB} = 147 Hz, 4F); ^{13}C NMR, δ 128.0, 128.3, 128.6, 128.8, 129.6, 136.1, 136.3, 138.9, 141.0 (m, J = 18.5 Hz), 142.0 (m).

*3.2.24. 1-Bromo-2-pentafluorosulfanylethane (**24**)*

^{1}H NMR, δ 4.06 (m, 2H), 3.73 (m, 2H); ^{19}F NMR, δ_A 81.0 (p, 1F), δ_B 63.7 (d, J_{AB} = 144 Hz, 4F).

*3.2.25. 2-Bromo-1-pentafluorosulfanylhexane (**25**) [24]*

^{1}H NMR, δ 4.46–4.38 (m, 1H), 4.3–3.92 (m, 2H), 2.12–1.98 (m, 1H), 1.90–1.76 (m, 1H), 1.66–1.22 (m, 7H); ^{19}F NMR, δ_A 82.8 (p, 1F), δ_B 65.4 (d, J_{AB} = 146 Hz, 4F); ^{13}C NMR, δ 77.4 (m), 47.2 (m, J = 4.2 Hz), 37.8, 29.5, 22.0, 14.1; HRMS (EI): Calcd for $C_6H_{12}SF_5Br$: 289.9763. Found: 289.9763 (monoisotopic).

*3.2.26. 2-Bromo-1-pentafluorosulfanylheptane (**26**)*

^{1}H NMR, δ 4.46–4.34 (m, 1H), 4.3–3.9 (m, 2H), 2.1–1.96 (m, 1H) 1.92–1.74 (m, 1H), 1.66–1.4 (m, 2H), 1.38–1.2 (m, 7H); ^{19}F NMR, δ_A 82.8 (p, 1F), δ_B 67.4 (d, J_{AB} = 147 Hz, 4F).

*3.2.27. 2-Bromo-1-pentafluorosulfanyloctane (**27**)*

^{1}H NMR, δ 4.46–4.36 (m, 1H), 4.28–3.92 (m, 2H), 2.1–1.96 (M, 1H), 1.9–1.76 (m 1H), 1.4–1.2 (m, 11H); ^{19}F NMR, δ_A 82.9 (p, 1F), δ_B 65.4 (d, J_{AB} = 148 Hz, 4F); HMRS: Calcd for $C_8H_{16}SF_5Br$: 318.0076. Found: 318.0067 (monoisotopic).

*3.2.28. 2-Bromo-1-pentafluorosulfanylcyclohexane (**28**)*

^{1}H NMR, δ 4.59 (m, 1H), 4.43 (m, 1H), 4.1 (m, 2H), 2.4–2.1 (m, 4H), 1.9–1.2 (m, 2H); ^{19}F NMR, δ_A 85.2 (p, 1F), δ_B 56.9 (d, J_{AB} = 141 Hz, 4F).

*3.2.29. (E)-4-Bromo-5-pentafluorosulfanyloct-4-ene (**29**)*

^{1}H NMR, δ 2.82 (t, J = 8 Hz, 2H), 2.63 (t, 8 Hz, 2H), 1.74–1.57 (m, 4H), 0.95 (td, J = 8, 2.5 Hz, 6H); ^{19}F NMR, δ_A 86.3 (p, 1F), δ_B 67.4 (d, J_{AB} = 150 Hz, 4F); HMRS: Calcd for $C_8H_{14}SF_5Br$: 315.9920. Found: 315.9920 (monoisotopic).

*3.2.30. (E)-2-Bromo-1-pentafluorosulfanylprop-1-en-3-yl acetate (**30**)*

^{1}H NMR, δ 6.93 (p, 1H), 5.02 (s, 2H), 2.12 (s, 3H); ^{19}F NMR, δ_A 79.8 (p, 1F), δ_B 67.0 (d, J_{AB} = 152 Hz, 4F); ^{13}C NMR, δ 170.0, 141.2 (p, J = 21.5 Hz), 131.7 (t, J = 6 Hz), 62.8, 20.6.

*3.2.31. 1-Bromo-1-phenyl-2-pentafluorosulfanylethene (**31**) [29]*

^{1}H NMR, δ 7.46–7.28 (m, 5H), 7.1 (p, J = 7.5 Hz, 1H); ^{19}F NMR, δ_A 80.5 (p, 1F), δ_B 67.4 (d, J_{AB} = 153 Hz, 4F); ^{13}C NMR, δ 135.4 (d, J = 20 Hz), 132.7, 127.8 (p, J = 7 Hz), 125.2, 123.7, 122.8; HRMS: Calcd for $C_8H_6SF_5Br$: 307.9294. Found: 307.9294 (monoisotopic).

3.3. 1,1-Dimethoxy-2-pentafluorosulfanylethane

A solution of 1-acetoxy-1-chloro-2-pentafluorosulfanylethane (**11**) (3.2 g, 12.9 mmol) and 8 mL of anhydrous methanol was stirred while maintaining the temperature at 50 °C overnight. The solution was then treated with 5 mL of water and partitioned with 20 mL Et_2O. The layers were separated and the ether layer washed two times with 10 mL portions of water. The aqueous layers were combined and extracted with 10 mL of ether. Then the ether layers were combined, dried with $MgSO_4$, and the ether removed under reduced pressure to provide 2.2 g (79%) of acetal: ^{1}H NMR, δ 4.85 (t, J = 5 Hz, 1H), 3.76 (dp, J = 9, 5 Hz, 2H), 3.38 (s, 6H); ^{19}F NMR, δ_A 83.5 (p, 1F), δ_B 66.2 (d, J_{AB} = 148 Hz, 4F).

3.4. Peroxymonosulfuric acid (Caro's acid) [36]

Finely ground ammonium persulfate (11.6 g, 51 mmol) was added in three equal portions over a period of several minutes to an ice cold solution of conc. H_2SO_4 (16 M, 8 mL, 2.85 equiv.)

and ice water (1.7 mL, 1.85 equiv.). The solution was brought to RT and stirred until a clear homogeneous solution was obtained. Gentle heating may aid in the dissolution of the persulfate. The solution thus obtained was used for the following preparation.

3.5. Methyl 2-pentafluorosulfanylacetate (**32**) [14]

A flask containing 1,1-dimethoxy-2-pentafluorosufanylethane in 10 mL of anhydrous methanol was fitted with a pressure equalizing dropping funnel containing 6 mL (2 equiv.) of Caro's acid. The peroxymonosulfate solution was added dropwise to the stirred solution of the acetal and the solution was allowed to stir overnight at 45 °C. The solution was treated with 5% aqueous $NaHCO_3$ followed by 10 mL of water. The combined aqueous layers were back extracted with Et_2O (10 mL) and the ether layers were combined and dried with $MgSO_4$. Solvent was removed under reduced pressure to provide 1.29 g of ester 32 in 63% yield [14]: ^{1}H NMR, δ 6.89 (p, J = 8 Hz, 2H), 3.83 (s, 3H); ^{19}F NMR, δ_A 78.9 (p, 1F), δ_B 70.8 (d, J_{AB} = 148 Hz, 4F); ^{13}C NMR, δ 163.0, 70.3 (p, J = 17 Hz), 53.51; MS: m/z 169, 127, 89, 56, 41, 28.

3.6. Methyl 4-pentafluorosulfanyl but-2-enoate (**33**) [33]

A solution of methyl 3-chloro-4-pentafluorosulfanylbutyrate (**17**) in methanol was prepared and 1 equiv. of NaOMe/MeOH solution was added dropwise to result in a yellow solution. After stirring for 1 h, the solution was partitioned with ether and water. The ether layer was washed with small portions of water and the ether layer was dried with $MgSO_4$, filtered, and the solvent removed under reduced pressure to provide 0.43 g (76%) of unsaturated ester 33 as a colorless liquid [33]: ^{1}H NMR, δ (p, J = 7.5 Hz, 1H), 6.09 (dt, J = 16, 1.2 Hz, 1H), 4.38 (dd, J = 7.5, 1 Hz, 2H), 3.79 (s, 3H); ^{19}F NMR, δ_A 80.5 (p, 1F), δ_B 65.9 (d, J_{AB} = 143 Hz, 4F); ^{13}C NMR, δ 165.5, 135.2 (p, J = 4.5 Hz), 128.5, 71.6 (p, J = 16 Hz), 52.3.

3.7. 1-Pentafluorosulfanylpropan-2-one (**34**) [34]

A mixture of the 2-acetoxy-2-chloro-1-pentafluorosulfanylpropane (**18**) (2.9 g, 11.0 mmol) in 10 mL of water was stirred thoroughly and 1 molar equiv. of K_2CO_3 (15 mL, 5% w/v soln) was added dropwise to the solution. The resulting yellow solution color disappeared within 10 min and the solution was refluxed for 1 h. The solution was extracted with three 15 mL portions of CH_2Cl_2. The combined extracts were dried with $MgSO_4$, filtered, and solvent removed under reduced pressure to afford 1.5 g (74%) of ketone 33 as a liquid: ^{1}H NMR, δ 4.33 (p, J = 8 Hz, 2H), 2.41 (s, 3H); ^{19}F NMR, δ_A 76.9 (p, 1F), δ_B 68.3 (d, J_{AB} = 147 Hz, 4F).

3.8. 1-Pentafluorosulfanylhex-1-yne (**35**)

To a solution of *E*-2-chloro-1-pentafluorosulfanylhex-1-ene (**21**) (3.8 g, 15.5 mmol) in DMSO (60 mL) was added $LiOH{\cdot}H_2O$ (5 equiv., 3.3 g). The mixture was stirred for 2 h at RT, and then the mixture was poured into ice water, neutralized with 2 M HCl, and extracted with ether twice. The organic layers were combined, washed with brine, and dried over $MgSO_4$. The solvent was removed under reduced pressure very carefully without heating, and then the residue was distilled to give 1.3 g (40%) of alkyne product 35: ^{1}H NMR, δ 0.94 (t, J = 7.5 Hz, 3H), 1.44 (m, 2H), 1.58 (m, 2H), 2.32 (m, 2H); ^{19}F NMR, δ_A 77.8 (p, 1F), δ_B 83.0 (d, J_{AB} = 180 Hz, 4F).

Acknowledgment

Support of this research in part by the National Science Foundation is gratefully acknowledged.

References

[1] R.W. Winter, G.L. Gard, in: J.S. Thrasher, S.H. Strauss (Eds.), Inorganic Fluorine Chemistry—Toward the 21st Century, American Chemical Society, Washington, 1994, pp. 128–147.
[2] D. Lentz, K. Seppelt, in: K. Akiba (Ed.), Chemistry of Hypervalent Compounds, Wiley–VCH, New York, 1999, pp. 295–326.
[3] R.D. Verma, R.L. Kirchmeier, J.M. Shreeve, in: A.G. Sykes (Ed.), Advances in Inorganic Chemistry, Academic Press, San Diego, 1994, pp. 125–169.
[4] R.W. Winter, R. Dodean, G.L. Gard, in: V.A. Soloshonok (Ed.), Fluorine Containing Synthons, ACS Publication Division and Oxford University Press, Washington, DC, 2005, pp. 87–118.
[5] W.A. Sheppard, J. Am. Chem. Soc. 84 (1962) 3072–3076.
[6] R. Salmon, Patent WO 9306089 (1993).
[7] M.H. Howard Jr., T.M. Stevenson, Patent WO 9516676 (1995).
[8] W.A. Sheppard, J. Am. Chem. Soc. 84 (1962) 3064–3072.
[9] R.D. Chambers, R.C.H. Spink, Chem. Commun. (1999) 883–884.
[10] R.D. Bowden, P.J. Comina, M.P. Greenhall, B.M. Kariuki, A. Loveday, D. Philp, Tetrahedron 56 (2000) 3399–3408.
[11] A.M. Sipyagin, C.P. Bateman, Y.-T. Tan, J.S. Thrasher, J. Fluorine Chem. 112 (2001) 287–295.
[12] J.R. Case, N.H. Ray, H.L. Roberts, J. Chem. Soc. (1961) 2066–2070.
[13] J. Wessel, G. Kleemann, K. Seppelt, Chem. Ber. 116 (1983) 2399–2407.
[14] R. Winter, G.L. Gard, J. Fluorine Chem. 66 (1994) 109–116.
[15] A.V. Fokin, Y.N. Studnev, V.P. Stolyarov, V.G. Chilikin, G.A. Prigorelov, Russ. Chem. Bull. 45 (1996) 2804–2806.
[16] S. Ait-Mohand, W.R. Dolbier Jr., Org. Lett. 4 (2002) 3013–3015.
[17] T.A. Sergeeva, W.R. Dolbier Jr., Org. Lett. 6 (2004) 2417–2419.
[18] H.W. Sidebottom, J.M. Tedder, J.C. Walton, Trans. Faraday Soc. 65 (1969) 2103–2109.
[19] J. Steward, L. Kegley, H.F. White, G.L. Gard, J. Org. Chem. 34 (1969) 760–762.
[20] C. Mir, R. Debuhr, C. Haug, H.F. White, G.L. Gard, J. Fluorine Chem. 16 (1980) 373–383.
[21] R. Winter, G.L. Gard, J. Fluorine Chem. 102 (2000) 79–87.
[22] R.W. Winter, R. Dodean, J.A. Smith, R. Anilkumar, D.J. Burton, G.L. Gard, J. Fluorine Chem. 122 (2003) 251–253.
[23] R.W. Winter, G.L. Gard, J. Fluorine Chem. 125 (2004) 549–552.
[24] G.S. Lal, K. Minnich, Abstracts of Papers of the American Chemical Society 228: U127-U137, 620 ORGN Part 2, August 22, 2004.
[25] Y. Takeyama, Y. Ichinose, K. Oshima, K. Utimoto, Tetrahedron Lett. 30 (1989) 3159–3162.
[26] R. Winter, P.G. Nixon, G.L. Gard, D.H. Radford, N.R. Holcomb, D.W. Grainger, J. Fluorine Chem. 107 (2001) 23–30.
[27] E.I. duPont de Nemours & Co., US Patent 3102903 (1961).

[28] V. Beraud, Y. Gnanou, J.C. Walton, B. Maillard, Tetrahedron Lett. 41 (2000) 1195–1198.
[29] C. Merrill, Ph.D. Dissertation, University of Washington, 1962, pp. 76–82.
[30] R.W. Winter, R. Dodean, L. Holmes, G.L. Gard, J. Fluorine Chem. 125 (2004) 37–41.
[31] Q.C. Wang, H.F. White, G.L. Gard, J. Fluorine Chem. 13 (1979) 455–459.
[32] J.M. Canich, M.M. Ludvig, W.W. Paudler, G.L. Gard, J.M. Shreeve, Inorg. Chem. 24 (1985) 3668–3670.
[33] V.K. Brel, Synthesis (2006) 339–343.
[34] G. Kleemann, K. Seppelt, Chem. Ber. 112 (1979) 1140–1146.
[35] All compounds that do not have a reference are novel.
[36] A. Nishihara, I. Kibota, J. Org. Chem. 33 (1968) 2525–2526.