Polyfluorinated Oxaziridines: Synthesis and Reactivity

Viacheslav A. Petrov*,† and Giuseppe Resnati*,‡

DuPont Central Research and Development, P.O. Box 80328, Wilmington, Delaware 19880-0328, and C.N.R.—Centro Studio Sostanze Organiche Naturali, Dipartimento Chimica, Politecnico, 7, via Mancinelli, I-20131 Milano, Italy

Received November 9, 1995 (Revised Manuscript Received April 15, 1996)

Contents

I. Introduction

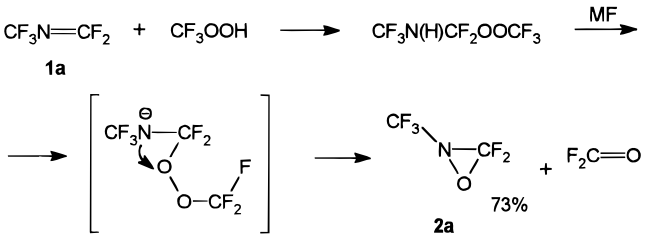
Oxaziridines are three-membered heterocyclic compounds containing oxygen, nitrogen, and carbon. They were first described in mid-1950s,[1−3] but the first perfluorinated example was reported in mid-1970s.[4] Some scattered papers in the 1980s have provided evidence of the unusual reactivity and unique properties of these perfluorinated heterocycles. It is only in the last five years, however, that a strong focus on the area allowed the unique properties of polyfluorinated oxaziridines to be recognized. For instance, perfluorinated oxaziridines as oxidants are much closer to dioxiranes than to hydrocarbon oxaziridines. This is a consequence of the dramatic effect of electon-withdrawing perfluoroalkyl groups.

While the chemistry of hydrocarbon oxaziridines has been reviewed in several papers,[5−10] the current work is the first attempt to provide a comprehensive survey of the synthesis, physical properties, and reactions of poly- and perfluorinated oxaziridines.

II. Synthesis

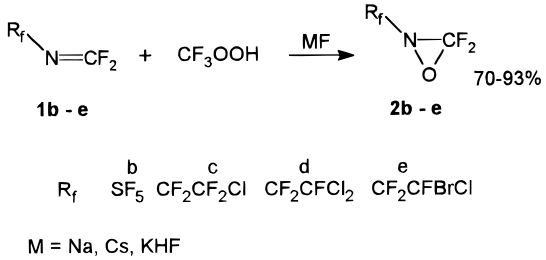
The synthesis of perfluoro-2-methyloxaziridine (**2a**), the first representative of perfluorinated oxaziridines, was performed in two steps (Scheme 1): addition of trifluoromethyl hydroperoxide to perfluoro-2-azapropene (**1a**) gave the adduct $CF_3OOCF_2N(H)CF_3$ which was then cyclized with NaF.[4]

Scheme 1



The reactions of various metal fluorides with this open-chain intermediate were investigated in full detail and KHF_2 was found to be the most suitable reagent for its conversion to oxaziridine **2a**. The yield of the oxaziridine relates to the activity of the metal fluoride used and decreases with the increase in nucleophilicity of the metal fluoride: KHF_2 > NaF ≫ KF > CsF.[11] The mechanism postulated by the authors involves abstraction of hydrogen to give an aza anion which then undergoes intramolecular cyclization with elimination of CF_3O^-, decomposition of which forms carbonyl fluoride.

2-(Pentafluorothio)-3,3-difluorooxaziridine[12] (**2b**) and a series of (polyfluoroethyl)-3,3-difluorooxaziridines[13] **2c**−**e** were prepared in a similar manner (eq 1).



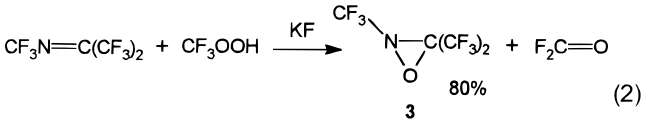
A modification of this procedure was used for the preparation of di- and trisubstituted fluorinated oxaziridines.[14,15] Internal azaalkenes do not react with trifluoromethyl hydroperoxide without a catalyst; however, the corresponding oxaziridines have been synthesized in a one-pot synthesis when dry KF was employed as a catalyst and reagent for absorption of HF.[14] By using this procedure 2,3,3-tris(trifluoromethyl)oxaziridine (**3**) was obtained in 80% yield (eq 2). Other compounds which generate trifluoromethylperoxy anion on reaction with a base can be also used for preparing fluorinated oxaziridines.

† DuPont, Wilmington.
‡ C.N.R., Milano.

S0009-2665(94)01146-5 CCC: $25.00

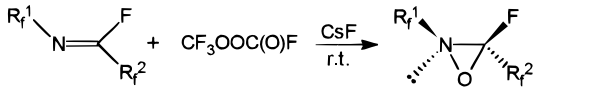
Viacheslav A. Petrov carried out his undergraduate research under the direction of academician I. L. Knunyats in 1979. He received his Ph.D. in Organic Chemistry in 1983 from the Institute of Organo-Element Compounds AN USSR (Moscow, USSR). His Ph.D. research was carried out in the Laboratory of Fluoroorganic Compounds under supervision of Professor L. S. German. In 1989, after 11 years of experience with this research team, he joined a group of Professor Darryl D. DesMarteau at Clemson University, Clemson, SC, as a Professor Assistant, where his research resulted in development of a new method of synthesis of polyfluorinated oxaziridines and investigation of reactions of these compounds. Clemson was the place where the work on the utilization of polyfluorinated oxaziridines in a fine organic synthesis was started in colaboration with Dr. Guiseppe Resnati and Dr. Vittorio Montanari. In 1992 he joined the Fluoroproduct Group of DuPont Centeral Research and Development organization. His research interests focus upon the electrophilic reactions of poly- and perfluorinated compounds, especially transformations, catalyzed by Lewis acids, along with the synthesis and reactivity of small-ring systems.

Giuseppe Resnati was born in Monza, Italy, in 1955 and received his Ph.D. at the University of Milano. In 1980 he entered the Chemical Research Department of Farmitalia-Carlo Erba (Milano) and two years later he assumed his present position at the Centre for the Study of Organic Natural Substances at the National Research Council of Italy. He was a contract professor at the University of Padova, Faculty of Pharmacy (1987–1989); NATO Fellow at Clemson University (Clemson, SC) (1990–1991); and a visiting professor at the Universitè Paris XI (1993). He is serving as coordinator of a European Community Network on fluoroorganic compounds. His research interests include asymmetric synthesis and biotransformations of fluorinated compounds, the relevance of fluorine to biological processes and drug activity, NMR and mass spectrometry of fluorinated molecules, and synthetic methods utilizing fluorinated reagents.



(2)

Perfluoro-*cis*-2,3-dialkyloxaziridines **5a**−**c** were prepared from the corresponding imines **4a**−**c** using $CF_3OOC(O)F$ as a source of trifluoromethylperoxy anion (eq 3).[15] It is interesting that the reaction is completely diastereoselective. *cis*-Oxaziridines **5** are formed exclusively from imines **4** having (*Z*) configuration. $CF_2(OF)_2$ was also used for the oxidation of internal imines. Oxaziridine **5c** was formed in low yield from its reaction with perfluoro-5-azanon-4-ene (**4c**). The main reaction product was perfluorodibutylamine,[16] the product of fluorination of starting imine (dibutylamine/oxaziridine ratio 78:22).[15]

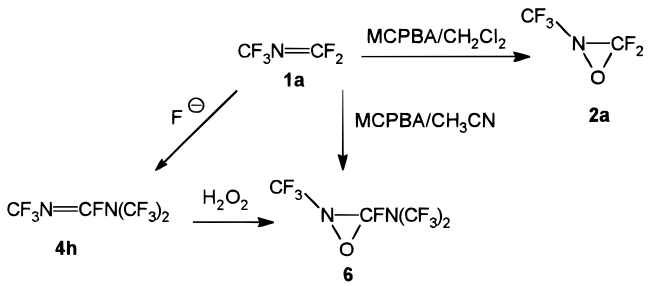


(3)

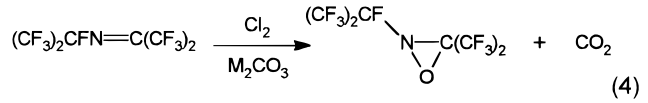
	R_f^1	R_f^2	Yield %
a	*i*-C_3F_7	CF_3	30
b	*n*-C_3F_7	C_2F_5	85
c	*n*-C_4F_9	*n*-C_3F_7	82

Perfluoro-2-methyl-3-(*N*,*N*-dimethylamino)oxaziridine (**6**) can be prepared in moderate yield by oxidation of the dimer **4h** of perfluoro-2-azapropene with 50% hydrogen peroxide (Scheme 2).[17] The presence of water is a serious limitation since polyfluorinated azaalkenes are extremely sensitive to hydrolyses.[18]

Scheme 2



Another patent[19] discloses the synthesis of trisubstituted oxaziridines by reaction of imines with chlorine gas and an alkali metal carbonate (eq 4).



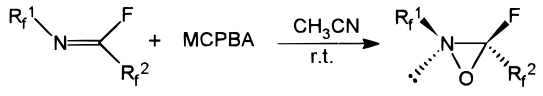
(4)

M = K, Cs

m-Chloroperbenzoic acid (MCPBA) is the reagent of choice for the preparation of hydrocarbon oxaziridines,[5,6] and it has also been employed for synthesizing partially halogenated oxaziridines. For example, 2-*tert*-butyl-3-(2,2-dibromoethyl)oxaziridine and 2-*tert*-butyl-3-(trichloromethyl)oxaziridine were prepared in 56 and 98% yield, respectively, by oxidation of corresponding aldimines with MCPBA in methylene chloride.[20] The same methodology was used to prepare some partially fluorinated *N*-sulfonyloxaziridines.[21] A biphasic system, MCPBA in methylene chloride and $NaHCO_3$ or K_2CO_3 in water, was utilized for preparing optically active oxazirirdines such as 2-sulfamyl-3-(pentafluorophenyl)oxaziridine[22] and *N*-(phenylsulfonyl)-3-(3,3-difluorocamphoryl)oxaziridine[23] from the corresponding imines.

MCPBA in CH_2Cl_2 solution was also used to convert perfluoro-2-azapropene (**1a**) into the corre-

sponding oxaziridine **2a** (50% yield) (Scheme 2).[24] Perfluoro-2-azapropene (**1a**) is known to form a dimer in the presence of fluoride ion;[18] therefore, it is not surprising that when the reaction is carried out in acetonitrile, a more polar solvent, oxaziridine **6** is obtained as the only product. This indicates that the rate of dimerization of this imine with fluoride anion is much higher than the rate of its reaction with MCPBA. Perfluorinated internal imine **4c** does not react with MCPBA in CH_2Cl_2 under similar conditions. A more polar solvent such as acetonitrile is required for oxidation of internal azaalkenes. For instance, the reaction between imines **4a**−**c** and pure MCPBA proceeds readily at ambient temperature and results in the formation of oxaziridines **5a**−**c** in 40−80% isolated yield (eq 5).[24] As observed previously for the oxidation of imines **4** with fluoroperoxycarbonate (eq 3), *cis*-oxaziridines are formed exclusively in the reaction of (*Z*)-imines with MCPBA.

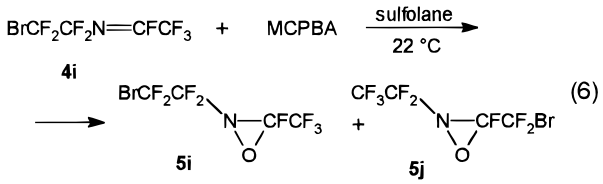


4a - g **5a - g** (5)

	R_f^1	R_f^2	Yield %
a	*i*-C_3F_7	CF_3	38
b	*n*-C_3F_7	C_2F_5	80
c	*n*-C_4F_9	*n*-C_3F_7	68
d	*n*-C_6F_{13}	*n*-C_5F_{11}	77
e	*n*-C_5F_{11}	*n*-C_4F_9	95
f	CF_3	CF_3	
g	CF_3	*n*-C_3F_7	

The reaction is slightly exothermic. Due to the low solubility of oxaziridines in organic solvent, the product (purity > 95%) can be isolated by separation of the fluoroorganic layer and washing to remove the solvent.[24] This relatively simple procedure was used to prepare a large number of fluorinated oxaziridines (eq 5).[24−26]

In the reaction of MCPBA with unsymmetrical imine **4i**, a mixture of isomeric oxaziridines **5i**,**j** was obtained (eq 6). This is further evidence for the presence of fluoride anion in the reaction media.[26]



4i **5i** **5j** (6)

5i : **5j** = 55 : 45

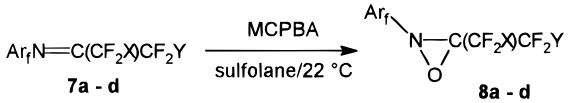
On the other hand, no migration of the C=N bond was observed in the reaction of perfluoro-2-azabut-2-ene and perfluoro-2-azahex-2-ene, (**4f** and **4g**), respectively, with MCPBA (eq 5).

While syntheses of fluorinated oxaziridines through oxidation of corresponding imines are similar to those of corresponding non-fluorinated analogues, the syntheses of starting perfluorinted imines are quite specific. Terminal imines of type **1** are made either by pyrolysis of the corresponding oxazetidines[18] or by radical addition of CF_2=N−X (X = Cl, Br) to fluorinated ethylenes.[13] In both routes the yields of products are quite high (80−95%), but the starting materials are rather exotic. Two approaches to internal imines of type **4** are based on reactions of commercially available perfluorinated tertiary amines which themselves are produced by electrochemical fluorination and readily available from distributors such as Aldrich Co. Pyrolysis of $(R_f)_3N$ (R_f = C_2F_5, C_3F_7, C_4F_9) at 650 °C in a flow system results in formation of CF_3N=CFR_f' (R_f' = CF_3, C_2F_5, C_3F_7).[27] Unfortunately, the isolation procedure includes reaction of crude product with anhydrous HF (2 days at 20 °C) followed by the reaction of $(R_f)_2NH$ formed with dry KF (24 h at 20 °C). Despite a high yield of imines (40−67%) purification step is long and requires handling of anhydrous HF.

Recently it was found that the cleavage of perfluorinated amines can be achieved at much lower temperature by using antimony pentafluoride as catalyst. The reaction between amine $(R_f)_3N$ and SbF_5 proceeds at 100−150 °C and produces a mixture of fluoro imine R_fN=CFR_f' (R_f = C_2F_5, C_3F_7, C_4F_9; R_f' = CF_3, C_2F_5, C_3F_7) and perfluoroalkane R_fF. Corresponding imines were isolated in 60−85% yield by fractionation.[28] A number of imines were prepared by reaction of amine with SbF_5.[29−31] Since experimental data on this reaction are published in journals that are not readily available the typical procedure[28] for preparation of imines **4b**−**e** is given below.

Preparation of Perfluorinated Imines R_fN=CFR_f'. A mixture of 0.1−1 mol of amine and 10−15 mol % of SbF_5 was heated in stainless steel or Hastelloy cylinder for 20−24 h at 120−130 °C. The reactor was cooled to 20 °C, and the gaseous products were slowly vented out [*n*-C_3F_8 and *n*-C_4F_{10} for reaction of $(C_3F_7)_3N$ and $(C_4F_9)_3N$ respectively], reaction mixture was slowly (exothermic!) poured on ice to destroy the catalyst. The lower, fluoroorganic layer was separated, dried over P_2O_5, and fractionated using short distillation column: **4b**, yield 63%, bp 58.5 °C;[32] **4c**, yield 63−85%, bp 101 °C;[28] **4d**, yield 88.7%, bp 125−126/130 mmHg;[31] **4e**, yield 73%, bp 125−127 °C.[31]

N-Aryloxaziridines **8a**−**d** have been prepared through oxidation with water-free MCPBA of fluorinated arylimines **7** (eq 7).[25] These precursors were obtained by the reaction of $YCF_2(XCF_2)C$=NH with perfluorotoluene or pentafluoropyridine in the presence of CsF.



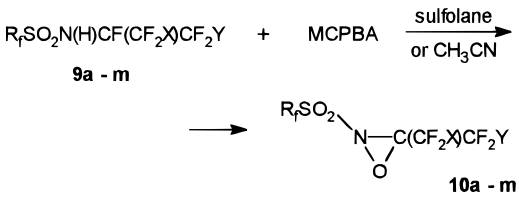
7a - d **8a - d** (7)

	Ar_f	X	Y	Yield (%)
a	*p*-C_5F_4N	F	F	60
b	*p*-$C_6F_4CF_3$	F	F	63
c	*p*- $C_6F_4CF_3$	F	Cl	89
d	*p*-C_5F_4N	Cl	Cl	70

Although structurally similar to arylimines **7a**−**d**, C_6F_5N=$C(CF_3)_2$ and *p*-H-C_6F_4N=$C(CF_3)_2$ surprisingly gave only a mixture of unidentified products in reaction with MCPBA.[25]

A quite unusual approach was used for the preparation of perfluoro-*N*-sulfonyloxaziridines **10a**−**m** (eq

8).[21] These compounds were produced in high yields

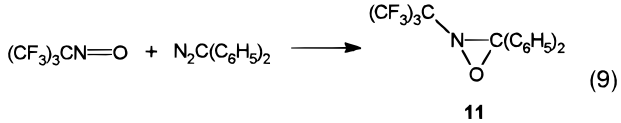


(8)

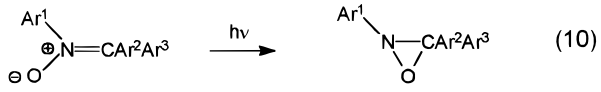
	R_f	X	Y	Yield (%)
a	CF_3	F	F	44
b	n-C_4F_9	F	F	48
c	C_2F_5	F	F	75
d	n-C_6F_{13}	F	F	82
e	CF_3	Cl	F	73
f	n-C_4F_9	Cl	F	57
g	n-C_6F_{13}	Cl	F	72
h	CF_3	Cl	Cl	26
i	n-C_4F_9	Cl	Cl	35
j	n-C_6F_{13}	Cl	Cl	41
k	F	F	F	44
l	F	F	Cl	50
m	F	Cl	Cl	43

by direct oxidation of *N*-sulfonylamides **9** with MCPBA in acetonitrile or sulfolane solution. In contrast to corresponding *N*-sulfonylimines, these starting materials are readily available by the reaction of imines of chlorofluoroacetones with R_fSO_2F.[21] Formation of oxaziridines in these reactions probably is the result of oxidation of the corresponding *N*-sulfonylimines, which are in equilibrium with *N*-sulfonylamides in polar solvents.

Finally, some nonoxidative methods for the synthesis of polyfluorinated oxaziridines have also been reported.[33] For example, diphenyldiazomethane was condensed[34,35] with perfluoro-*tert*-butylnitrosomethane to give the oxaziridine **11** (eq 9) and fluorinated arylnitrones were photochemically cyclized into corresponding oxaziridines (eq 10).[36,37]



(9)



(10)

Ar^1, Ar^2, Ar^3 = C_6H_5, C_6F_5

III. Physical and Spectroscopic Properties. Configurational Stability

Perfluorinated oxaziridines with small substituents are gases at ambient pressure (e.g. **2a**, bp −34.8 °C;[4] **2b**, bp 14.9 °C[12]) and become colorless liquid when the size of the alkyl groups increases (e.g. **3**, bp 24.98 °C;[14] **5d**, bp 67−68 °C/20 mmHg[24]). In general, fluorinated oxaziridines are indefinitely stable at ambient temperature with boiling points 10−30 °C higher than those of corresponding imines. Perfluoro-2,3-dialkyloxaziridines **5** and polyfluoro-*N*-sulfonyloxaziridine **10** can be purified by vacuum distillation at temperatures below 80 °C to avoid thermal isomerization (section IV.A). Polyfluoro-*N*-aryloxaziridines are thermally significantly less stable and should not be handled at a temperature above 30−40 °C to avoid isomerization into corresponding amides.[25]

Most of the polyfluorooxaziridines are colorless compounds; they are nonbasic and demonstrate strong oxidative properties (section IV.E).

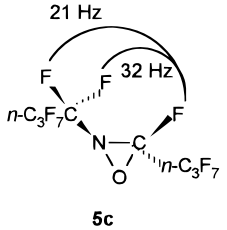
To the best of our knowledge there are no toxicological data in the literature on either polyfluorinated oxaziridines or perfluoroazaalkenes. Although now there is no reason to believe these materials to be significantly more toxic than their hydrocarbon analogues, reasonable precautions should be taken when handling these materials, as with any chemicals whose properties are not fully known. Since perfluorinated oxaziridines are potent oxidizing agents reactions with strong reducing agents can be quite energetic.

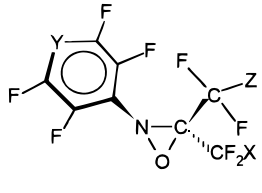
IR spectra of oxaziridines **2** bearing no substituents on the ring carbon atom exhibit a strong absorption band in the 1460−1430 cm^{-1} region. This absorption can be attributed to vibration of oxaziridine ring.[4,12,13] In perfluoro-2,3-dialkyloxaziridines **5** the absorption is slightly shifted and appears between 1420 and 1410 but at 1439 cm^{-1} for compounds **5a** having bulky i-C_3F_7 group at nitrogen.[14,24] In the case of polyfluorooxaziridines containing three perfluoroalkyl groups connected to the heterocycle,[14] the band has low intensity and appears in the region 1420−1400 cm^{-1}. In the mass spectra (EI) of polyfluorinated oxaziridines the parent ions are usually absent; however, CI mass spectra of these compounds exhibit a high-intensity M + 1 ion.[4,13,15,24−26]

Interesting information is obtained from ^{19}F NMR spectra of polyfluorinated oxaziridines. The nitrogen and carbon atoms in perfluoro-2,3-dialkyloxaziridines are stereogenic, and it results in the magnetic nonequivalence of fluorine atoms in CF_2 groups connected to these atoms.[15,22,24] The $^2J_{F,F}$ are approximately 210 and 300 Hz for CF_2N and $-CCF_2-$ groups, respectively. On the basis of the large values of $^4J_{F,F}$ across C−N bond of the ring 21 and 32 Hz for oxaziridine **5c** and as high as 60 Hz for **5a**, the configuration with two perfluoroalkyl group in a *trans* position was assigned to compounds **5** (Figure 1).[15,24,26]

In general, hydrocarbon oxaziridines are configurationally stable and have quite a high barrier of inversion at nitrogen (usually in range of 25−32 kcal/mol[38]), depending on the structure of oxaziridine. The high configurational stability of the pyramidal nitrogen in hydrocarbon oxaziridines makes it possible to isolate pure enantiomers.[39,40]

No data are reported on the barriers to nitrogen inversion in perfluoro-2,3-dialkyloxaziridines **5**. How-





8 X, Z = Cl, F; Y = N, CCF_3

Figure 1.

ever, the fact that epimerization of these compounds has not been observed either at ambient or elevated temperatures suggests that the barrier is higher than 25 kcal/mol.

A strong correlation between the electronegativity of the substituent bound to nitrogen and the barrier of inversion of pyramidal nitrogen was found.[41] It was reported that an electron-withdrawing sulfonyl group greatly reduces the configurational stability of pyramidal nitrogen in oxaziridines.[38,42] Specifically, introduction of a sulfonyl group decreases the free energy of nitrogen inversion from 32 kcal/mol, in *N*-alkyloxaziridines, to approximately 20 kcal/mol in *N*-sulfonyloxaziridines.

In view of this, the significant decrease in the barrier of nitrogen inversion in fluorinated oxaziridines due to replacement at nitrogen of a perfluoroalkyl group with a stronger electron-withdrawing group, such as R_fSO_2-, is not unexpected. Indeed, the ^{19}F NMR spectra of fluorinated *N*-(alkylsulfonyl)-oxaziridines **10a**−**c** exhibit broad resonances for alkyl groups connected to the carbon of oxaziridine ring.[21] These signals can be resolved at low temperature (−20 to −10 °C), and they collapse into a broad signal within a temperature range of 63−75 °C. This temperature dependence of the ^{19}F NMR spectra of these oxaziridines was explained through nitrogen inversion in the oxaziridine ring. Estimated free energies for this process are 14.9, 14.8, and 14.4 kcal/mol for **10a**, **10d**, and **10b**, respectively. A slight decrease of the energy barrier correlates with an increase in electronegativity of the R_fSO_2- group. The fact that nitrogen inversion has not been observed in oxaziridines **10k**−**m** having the less powerful electron-withdrawing FSO_2- group connected to nitrogen is also in agreement with this assumption.[21] These energies for nitrogen inversion are lower than those reported for hydrocarbon *N*-sulfonyloxaziridines (19.9−21 kcal/mol[38,42]) and might reflect the higher electronegativity of perfluoroalkylsulfonyl compared to alkylsulfonyl group. However, it could also be the result of different experimental techniques used for estimation of free activation energies of nitrogen inversion in fluorinated and hydrocarbon oxaziridines.

As expected, polyfluoro-*N*-aryloxaziridines are configurationally stable. The dynamic process found by ^{19}F NMR technique for a number of these compounds was explained in terms of restricted rotation of the bulky polyfluoroaryl group around the C−N bond[25] (Figure 1).

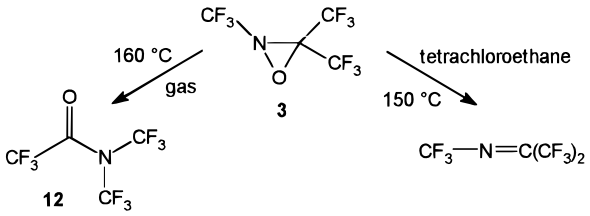
IV. Reactions

A. Thermal Rearrangements

Thermal rearrangements of hydrocarbon oxaziridines are well documented.[5−8] Usually these reactions proceed within a temperature range of 25−150 °C and lead to different products, typically nitrones or amides, formed through cleavage of C−O or N−O bonds of the heterocycle, respectively.

The thermal stability of partially fluorinated oxaziridines is quite low. For instance, oxaziridine **11** can be stored at 0 °C, but it readily decomposes at 50 °C[34] and 2-phenylsulfonyl-3,3-bis(trifluoromethyl)-

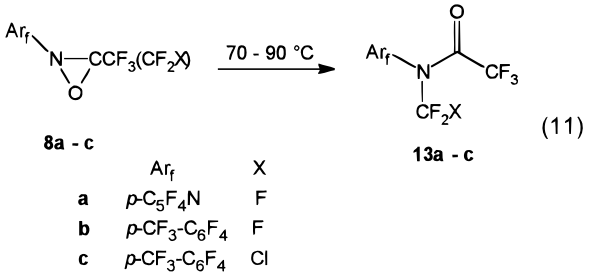
Scheme 3



oxaziridine is reported to decompose completely in several hours at room temperature.[21]

In contrast, perfluorinated alkyloxaziridines are more thermally stable and in general they start to rearrange only over 100 °C. There are no data on thermal stability of oxaziridines **2** obtained from terminal azaalkenes **1**. It has been reported that in the condensed phase, 2,3,3-trimethyloxaziridine **3**, obtained from an internal azaalkene, loses oxygen and gives the corresponding azaalkene at 150 °C (Scheme 3). In the gas phase, the same oxaziridine **3** undergoes a different reaction, slowly rearranging at 160 °C into perfluoro-*N*,*N*-dimethylacetamide **12**.[14]

Polyfluorinated *N*-aryloxaziridines **8a**,**b** are less stable. They readily rearrange at 70−90 °C (eq 11), giving the corresponding trifluoroacetamides **13a**,**b** in high yields[25] through a process similar to that observed for oxaziridine **3**. It is noteworthy that this

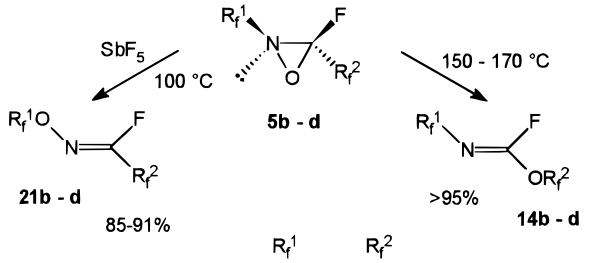


	Ar_f	X
a	*p*-C_5F_4N	F
b	*p*-CF_3-C_6F_4	F
c	*p*-CF_3-C_6F_4	Cl

reaction is regiospecific. For example nonsymmetrical oxaziridine **8c** under similar conditions gives only one amide **13c** which attests to the exclusive migration of the CF_2Cl group.[25]

In sharp contrast to oxaziridines **3** and **8**, containing three fluorinated substituents on the ring, thermal rearrangement of 2,3-dialkyloxaziridines **5b**−**d** proceeds at 150−170 °C and results in high yields of imidates **14** (Scheme 4).[43]

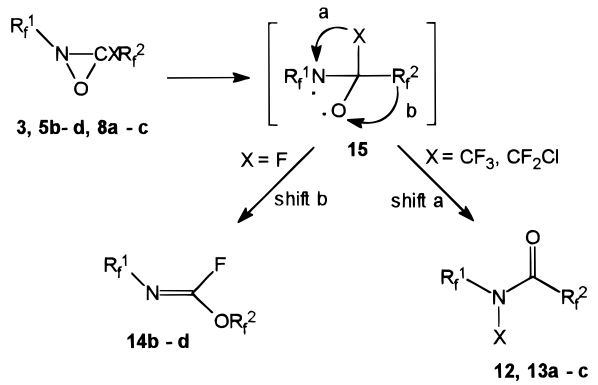
Scheme 4



	R_f^1	R_f^2
b	*n*-C_3F_7	C_2F_5
c	*n*-C_4F_9	*n*-C_3F_7
d	*n*-C_6F_{13}	*n*-C_5F_{11}

Despite differences in the structure of the products formed in thermal rearrangements of di- and trisubstituted oxaziridines, transformation of both classes of compounds can be rationalized on the basis of a

Scheme 5



common mechanism (Scheme 5). The biradical **15** can be postulated as a common intermediate for both processes. It forms as a result of selective homolytic cleavage of the N−O bond of the oxaziridine, the weakest in the ring. Further rearrangements can proceed in two different ways: migration of a polyfluoroalkyl group from carbon to nitrogen (shift a) or from carbon to oxygen (shift b). The first process is typical of trisubstituted oxaziridines and leads to the formations of amides **12** and **13**, whereas the second pathway is typical of disubstituted oxaziridines and affords imidates **14**. Another mechanism proposed for isomerization of 2,3,3-tris(trifluoromethyl)oxaziridine (**3**),[14] seems less likely, since it involves dissociation of the C−C bond, which obviously is stronger than N−O bond of the heterocycle, and generation of two independent radicals followed by recombination to give the final amide **12**.

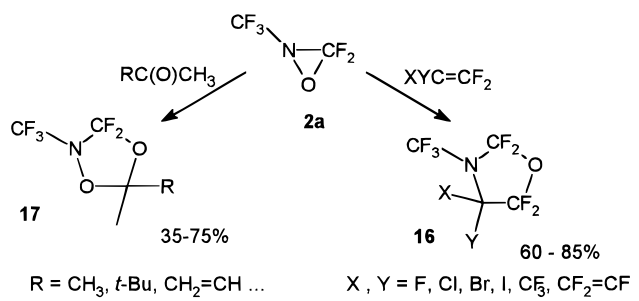
B. Cycloaddition Reactions

Cycloaddition reactions are typical of hydrocarbon oxaziridines and a number have been reported.[5−8] They occur through cleavage of the C−O, or sometimes C−N, bond of the oxaziridine ring. Among polyfluorinated oxaziridines cycloaddition reactions are rare and involve selective cleavage of the N−O bond.

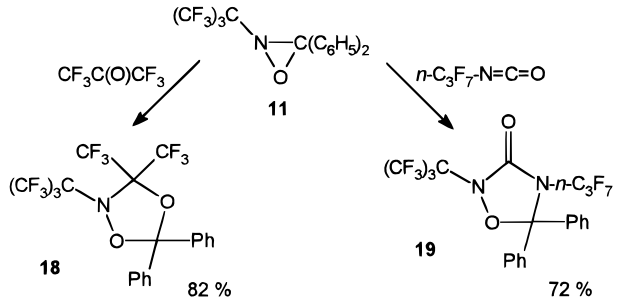
Most cycloadditions have been described for perfluoro-2-azapropene oxide **2a**. This oxaziridine reacts readily and regiospecifically with a number of fluoroethylenes under mild conditions (Scheme 6) yielding corresponding perhalo-3-(trifluoromethyl)-1,3-oxazolidines (**16**).[44,45]

Tetrafluoroethylene, bromotrifluoroethylene, iodotrifluoroethylene, 1,1-dichlorodifluoroethylene, hexafluoropropylene, and perfluoro-1,3-butadiene behave similarly in this reactions giving the corresponding 1,3-oxazolidines **16** in 25−85% yield. The reaction

Scheme 6



Scheme 7



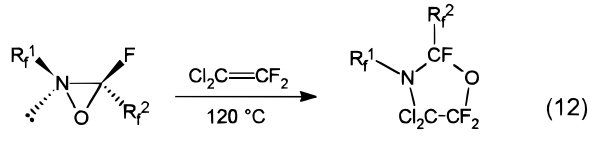
of oxaziridine **2a** with trifluoroethylene is not regiospecific. It gives a mixture of the two possible isomers perfluoro-4-*H*- and perfluoro-5-*H*-oxazolidines, in poor yield. These [2 + 3] cycloaddition reactions can proceed in two different ways through a mechanism involving the formation of a biradical intermediate in which the regioselectivity is determined by the relative stabilities of the biradical species or through the formation of the 1,3-dipolar species $CF_3N^+CF_2O^-$ where the ratio of isomeric products is controlled by the nucleophilic attack of the oxygen of the 1,3-dipole on the alkene. Both mechanisms can explain the observed regioselectivity. However the biradical mechanism helps to explain several quite "strange" results reported in the literature. Perfluoro-2-methyl-3-(*N*,*N*-dimethylamino)oxaziridine (**6**) gives copolymers with tetrafluoroethylene and hexafluoropropylene when exposed to UV irradiation or when treated with a radical initiator.[46,47] These copolymers have ether and amino linkages randomly distributed in the chain. Similarly, 2,3,3-trimethyloxaziridine (**3**) is capable of polymerizing tetrafluoroethylene at 85−160 °C.[14]

Attempts to carry out the cycloaddition of perfluoro-2-methyloxaziridine (**2a**) with $H_2C{=}CH_2$, CFCl=CFCl, perfluorocyclopentene, perfluoro-2-butene, acrylonitrile, and acetylene have failed.[45] The reaction of **2a** with 2-butene leads to the corresponding epoxide. Epoxides are likely intermediates in the formation of *cis*-3-hexene-2,5-dione and $CFBr_2C(O)F$ in the reaction of **2a** with 2,5-dimethylfuran and $CF_2{=}CBr_2$, respectively.[45]

2-Methyloxaziridine **2a** is the only perfluorinated oxaziridine reported to react with hydrocarbon ketones to form 1,3,4-dioxazolidines **17** (Scheme 6). The reaction does not occur with fluorinated ketones such as hexafluoroacetone.[45]

Partially fluorinated oxaziridine **11** has a different reactivity. With hexafluoroacetone a cycloaddition proceeds at 50−60 °C with cleavage of the C−N bond of the oxaziridine ring to give the corresponding 1,3,4-dioxazolidine **18**.[34] Similarly, cycloaddition to perfluoropropylisocyanate produces 1,2,4-oxadiazolidin-3-one **19** (Scheme 7).

The reactivity of higher perfluorinated oxaziridines in cyloaddition reactions with fluoroolefins is much lower than that of **2a** and depends on the size of the substituent at nitrogen. Yields of the corresponding perhalo-1,3-oxazolidine **20** in the reaction of perfluoro-2,3-dimethyloxaziridine (**5f**) with 1,1-dichlorodifluoroethylene are twice as high as with 2,3-dialkyloxazidines **5b**,**c** (eq 12).[26]



(12)

5b, c, f **20b, c, f**

	R_f^1	R_f^2	Yield %
b	n-C_3F_7	C_2F_5	10
c	n-C_4F_9	n-C_3F_7	12
f	CF_3	CF_3	20

C. Reactions with Lewis Acids

Hydrocarbon oxaziridines are basic enough to react with acids.[5−8] Interaction with strong protic acids typically leads to hydrolysis with formation of hydroxylamine and carbonyl compounds. However, depending on the substitution pattern, oxaziridines can be converted to nitrones[48] by treatment with anhydrous HCl or $AlCl_3$.

In contrast to hydrocarbon analogues, polyfluorinated oxaziridines do not react with protic acids and no formation of nitrones has been reported to date in their reactions with strong Lewis acids.

2-Azapropene oxide (**2a**) is the only fluorinated oxaziridine known to react with SbF_5 to form a cyclic dimer which structure has not been determined.[44] Perfluoro-*cis*-2,3-dialkyloxaziridines **5b**−**d** are stable to antimony pentafluoride at room temperature, but they readily rearrange at 100−110 °C, giving the corresponding oximes **21** (Scheme 4).[43] The rearrangement is stereospecific since oximes **21** having a (*Z*) configuration are exclusively formed starting from *cis*-oxaziridines **5**. The reaction occurs at a temperature well below that required for thermal isomerization (section IV.A). The proposed mechanism is similar to that suggested for isomerization of cyclic perfluorinated amines.[29] It begins with abstraction of a fluoride ion from the NCF_2 group by SbF_5 to give a cyclic immonium cation which opens through cleavage of the C−N bond of the heterocycle. The linear carbocation $R_f^2C(F){=}NOCF^+R_f^2$ is thus generated and its recombination with fluoride ion gives the final oximes **21**.

Unfortunately, no literature data are available on the reaction of polyfluoro *N*-aryl- and *N*-sulfonyloxaziridines with Lewis acids.

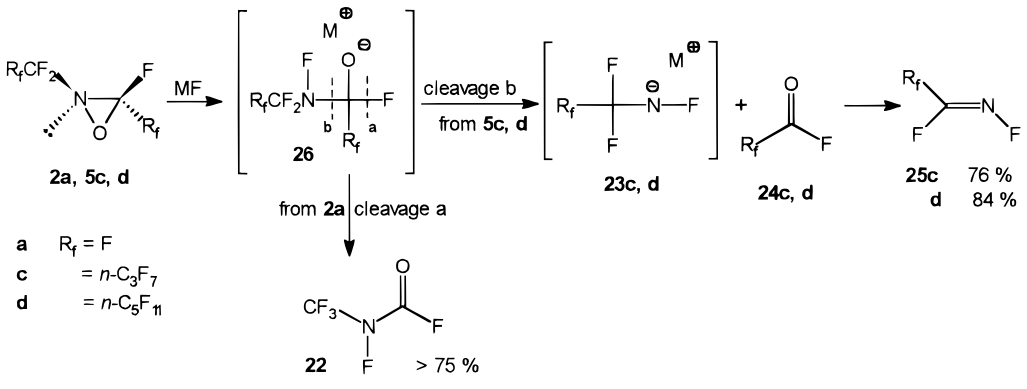
D. Reactions with Nucleophiles

In general, a nucleophile can attack the nitrogen, oxygen, or carbon atom of the oxaziridine ring. Thus oxaziridines can function as aminating, oxygenating, or alkylating agents. In the case of polyfluorinated oxaziridines, the latter pathway is the least likely, and to date only one example, the reaction of pentafluorothiooxaziridine **2b** with fluoride ion, has been rationalized in this way.[12] It is obvious that the site of attack of the nucleophile on the ring nitrogen or oxygen and the rate of the reaction are determined not only by the nature of the nucleophile, but also by the substitution pattern of the oxaziridine, especially at nitrogen. Steric hindrance makes attack at nitrogen difficult and shifts it to oxygen. For instance, hydrocarbon alkyl- and aryloxaziridines behave as aminating agents toward nitrogen and sulfur nucleophiles and even toward certain olefins.[49] However, introduction of a bulky or electron-withdrawing substituent on nitrogen drastically changes the reactivity and results in increase of the oxygenating properties of oxaziridines. *N*-Sulfonyloxaziridines,[7−10] *N*-phosphinoyloxaziridines,[50] and oxaziridinium salts[51,52] are known to behave as oxygenating agents. For polyfluorinated oxaziridines, attack at nitrogen is usually preferred by small nucleophiles (F^-, CN^-, RO^-, $RCOO^-$), while the attack at oxygen is typical for sterically hindered nucleophiles such as olefins and tertiary amines). Considering the steric hindrance of perfluoroalkyl groups, it is easy to conclude that polyfluorinated oxaziridines will have pronounced oxidative properties.

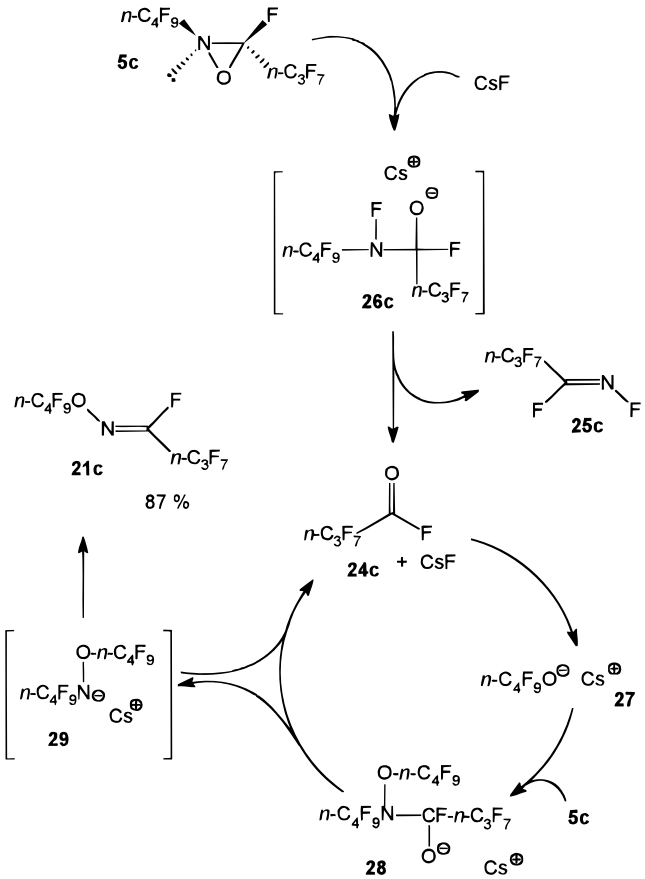
1. Alkali Metal Fluorides

It has been demonstrated that at room temperature alkali metal fluorides induce isomerization of perfluoro-2-methyloxaziridine (**2a**) into acyl fluoride **22** (Scheme 8). The yield of **22** depends on the metal fluoride employed. While compound **2a** is not reactive at room temperature toward NaF and KHF_2 the reaction with fused KF or CsF in the absence of solvent readily proceeds with formation of **22** and some unidentified polymeric materials.[11] The more sterically hindered 2-pentafluorothiooxaziridine (**2b**) remains nearly unchanged on treatment with KF under similar conditions. At 50 °C in a glass reactor formation of CF_3NO, SF_4 (identified as OSF_2), and COF_2 has been observed as major products.[12] Reac-

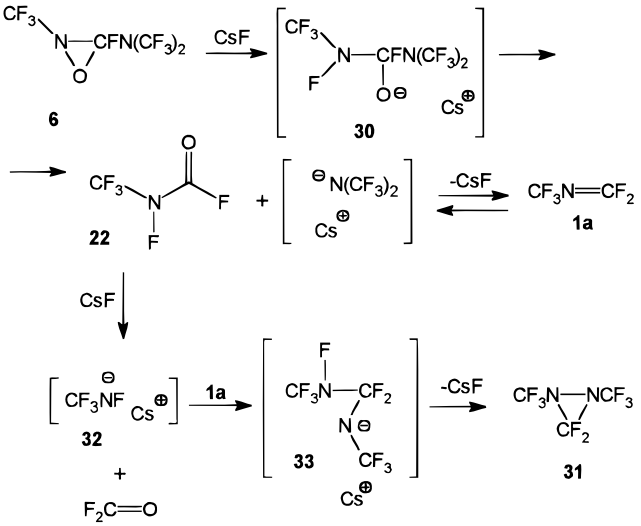
Scheme 8



Scheme 9



Scheme 10



tion with CsF occurs at room temperature, but leads to a mixture of low boiling point materials due to degradation of **2b**.[12]

Perfluoro-*cis*-2,3-dialkyloxaziridines **5** are even less reactive toward CsF and compounds **5c** and **5d** react with dry CsF in the absence of solvent only at temperatures of 100 °C or higher to give a 1:1 mixture of the corresponding *N*-fluoroimine **25** and acyl fluoride **24** (Scheme 8). The general mechanism of the reaction of oxaziridines **2a** and **5c**,**d** with metal fluorides involves as a first step attack of F^- on nitrogen of the oxaziridine ring and formation of oxy anion **26** as an intermediate. Starting from **2a**, this anion evolves through elimination of F^-, cleavage a, and acyl fluoride **22** is formed. In the case of 2,3-dialkyloxaziridines **5**, oxy anion **26** decomposes, yielding acyl fluorides **24c**,**d** and aza anions **23c**,**d**, cleavage b, which subsequently give *N*-fluoroimines **25c**,**d** through loss of fluoride anion.

Surprisingly, the reaction of oxaziridine **5c** with CsF in a polar solvent proceeds readily at 22 °C, giving an entirely different compound, i.e. oxime **21c**, as the only product.[43] A nucleophilic chain process was proposed to explain this result (Scheme 9).

As in the previous case, the reaction starts with the attack of fluoride anion on the nitrogen atom of the oxaziridine to give a mixture of *N*-fluoroimine **25c** and acyl fluoride **24c**. Then, perfluoro cesium *n*-butoxide **27** readily formed from **24c** and CsF reacts with **5c** to give oxy anion **28** which decomposes releasing the acyl fluoride **24c** and the aza anion **29**. The latter gives the final oxime **21c** by elimination of F^-. Acyl fluoride **24c** can react with CsF to produce cesium alkoxide **27** which can continue the catalytic cycle. The whole mechanism is based on the reasonable assumption that the rate of the reaction between oxaziridine **5c** and alkoxy anion **27** is higher than the rate of the reaction between oxaziridine **5c** and fluoride anion or aza anion **23c** (Scheme 8).

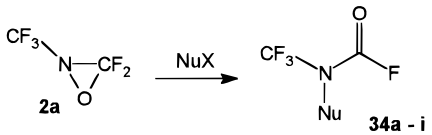
Finally, an unusual transformation has been found for perfluoroaminooxaziridine **6** which reacts with CsF at room temperature producing diaziridine **31** in moderate yield (Scheme 10).[53]

This reaction can be explained as resulting from the usual fluoride ion attack on the nitrogen atom of the oxaziridine ring producing the unstable oxy anion **30** which subsequently decomposes giving acyl fluoride **22** and cesium bis(trifluoromethyl)amide. Under the reaction conditions this salt can be in equilibrium with the corresponding imine **1a**. The well-known reaction between acyl fluoride **22** and CsF produces carbonyl fluoride and aza anion **32**, which is a sufficiently strong nucleophile to attack imine **1a** and give the new aza anion **33**. Cyclization of this anion to diaziridine **31** occurs through elimination of fluoride anion. It should be pointed out that the cyclization reaction of *N*-fluoro compounds giving diaziridines is well documented in the literature.[54]

2. O-Nucleophiles

The reaction between the perfluoro-2-methyloxaziridine (**2a**) and cesium trifluoromethoxide or cesium heptafluoroisopropoxide was first reported in 1979 (eq 13).[55]

At room temperature and without solvent, the oxygen nucleophile rapidly attacks the nitrogen atom of the heterocyclic ring to give the corresponding acyl fluoride **34a**,**b** in high yields. No reaction has been observed under similar conditions between **2a** and other fluorinated oxygen-centered nucleophiles such as CF_3CH_2OH, $(CF_3)_2CHOH$, or $(CF_3)_3COH$ in the presence of NaF. Interaction between **2a** and CF_3CH_2ONa is hard to control and it results in combustion.[55] On the other hand, some hydrogenated oxygen-centered nucleophiles such as CH_3OH, C_2H_5OH, $(CH_3)_2CHOH$, $(CH_3)_3COH$, and CH_3COOH react with **2a** in the presence of NaF as a scavenger of hydrogen fluoride to give the corresponding acyl fluoride de-



(13)

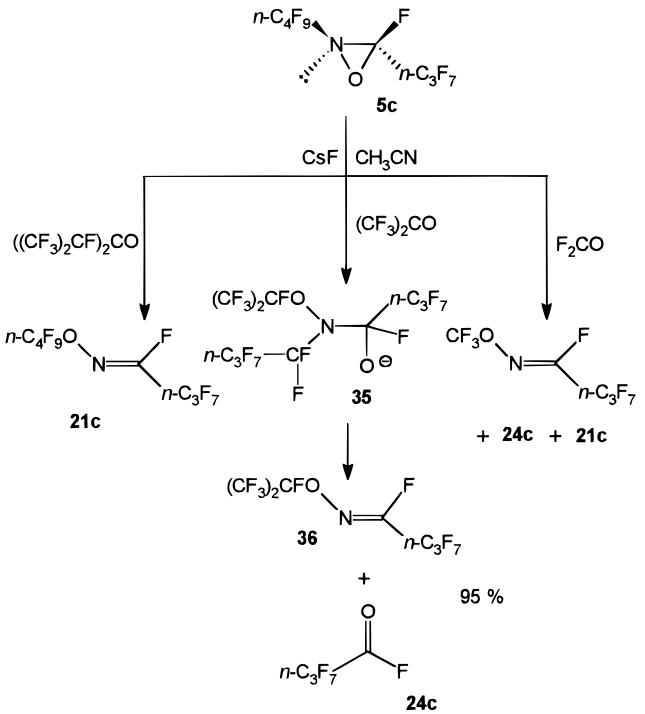
	NuX	Yield %
34a	CF_3OCs	80
b	$(CF_3)_2CFOCs$	81
c	CH_3OH	80
d	C_2H_5OH	81
e	$(CH_3)_2CHOH$	88
f	$(CH_3)_3COH$	93
g	CH_3COOH	32
h	C_2H_5SH	30
i	KCN	40

rivatives **34c**−**g** through the expected attack at nitrogen.

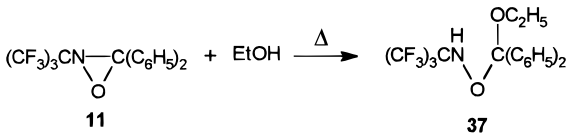
The product formed when the 2,3-dialkyloxaziridine **5c** reacts with fluorinated carbonyl compounds in the presence of cesium fluoride depends on reactivity of the carbonyl compound toward CsF (Scheme 11).[43] If it is low (e.g., perfluorodiisopropyl ketone), the reaction of the oxaziridine with fluoride ion occurs exclusively and the oxime **21c** is formed through the mechanism discussed above. If the carbonyl substrate easily adds fluoride ion, the corresponding cesium alkoxide attacks the nitrogen of the oxaziridine to give the acyclic intermediate **35**. Cleavage of the carbon−nitrogen bond in **35** leads to oxime **36** and acyl fluoride **24c** (1:1 ratio, 95% yield based on hexafluoroacetone). Both reactions described above occur with carbonyl substrates having an intermediate reactivity toward CsF to give a mixture of products, for example F_2CO.

The reactivity of partially fluorinated oxaziridines toward oxygen-centered nucleophiles is quite different. When 2-perfluoro-*tert*-butyl-3,3-diphenyloxaziridine (**11**) was reacted with ethanol, a selective attack

Scheme 11



at carbon occurred with cleavage of the C−N bond to give compound **37** (eq 14).[34]



(14)

Finally, interaction of polychloro- and polybromooxaziridines with sodium methoxide is not selective, and it usually leads to complex mixtures.[20] Under similar reaction conditions, some monochloro- and monobromooxaziridines gave vinyloxaziridines through elimination of HX.[20] No attack of CH_3O^- on the nitrogen atom of the oxaziridine ring was observed. This is an excellent example of the difference in reactivity toward nucleophiles of the oxaziridine ring in hydrocarbon and perfluorinated compounds.

3. Other Nucleophiles

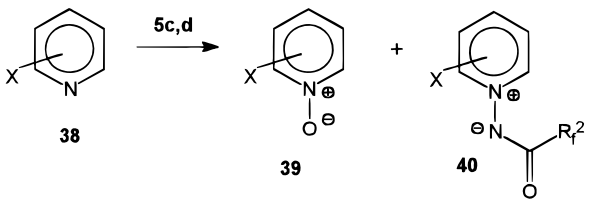
Examples of reactions of perfluorinated oxaziridines with other nucleophiles are not numerous. The reactions of perfluoro-2-methyloxaziridine (**2a**) have been studied with some sulfur,[55,56] carbon,[45,56] and nitrogen[55,56] nucleophiles (eq 13).

With C_2H_5SH, the expected ring-opening product **34h** is formed in moderate yield.[56] When the same oxaziridine **2a** is treated with CF_3SH in the presence of NaF, major reaction products are CF_3SSCF_3 and CF_3NCO. When KSCN is used as a nucleophile, CF_3NCO is the only isolated product. Initial attack of the nucleophile on the nitrogen atom of the heterocyclic ring was suggested to rationalize the formation of these products.

Potassium cyanide reacted slowly with the oxaziridine **2a** to give **34i** in moderate yield while 1-(trifluoromethyl)-3-(trimethylsilyl)carbodiimide and carbonyl fluoride were isolated in quantitative yield on reaction with trimethylsilyl cyanide. The mechanism of this latter transformation is not clear.

Interestingly, sodium azide does not react with **2a**. On the other hand, when **2a** was reacted with bis(trifluoromethyl)amine or diethylamine in the presence of NaF a complex mixture of products, not containing the expected adducts, was formed.

Pyridine derivatives **38** reacted with 2,3-dialkyloxaziridines **5c**,**d** readily at −60 °C and gave *N*-oxides **39** and pyridinium *N*-imines **40** (eq 15).[57,58]



(15)

X = alkyl, alkenyl ...

E. Oxygen-Transfer Reactions

Factors affecting the reactivity of oxaziridine ring toward nuclophiles have already been discussed (section IV.D). Here we examine some general aspects related to the oxidative properties of perfluorinated oxaziridines.

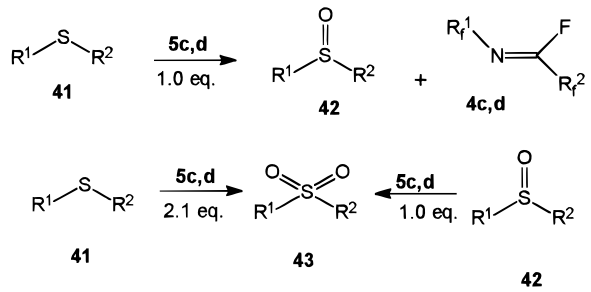
The presence of oxygen atom as a part of a three-membered ring is a feature shared by oxaziridines and several other commonly employed oxidizing agents, such as dioxiranes[59,60] and peroxometal complexes (V, Mo, W, Cr, etc.).[61,62] The Sharpless reagent [63] is probably one of the most recent and the most studied cyclic metal peroxides.

Previously noted, the presence of bulky substituents on the nitrogen of the oxaziridine ring increases the oxygenating properties of the heterocyclic system, so it is not surprising that perfluorinated oxaziridines are much more powerful oxidizing agents than hydrocarbon analogues. Actually, the reactivity of compounds **5** is closer to that of dioxiranes[59,60] than *N*-sulfonyloxaziridines.[7−10] Perfluorinated oxaziridines are more powerful oxidants than their hydrocarbon analogues and follow a well-documented trend. Indeed, trifluoroacetate of lead(IV),[64a] cobalt(III),[64b] thallium(III),[64c] mercury(II),[64d] and [bis(trifluoroacetoxy)iodo]benzene,[64e] trifluoroacetyl hypohalites,[64f] metalloporphirines with fluorinated residues,[64g] and methyl(trifluoromethyl)dioxirane[64h] are stronger oxidizers than the hydrocarbon analogues. Two of the most potent oxidizers in organic synthesis, cesium fluorooxysulfate and potassium persulfate are other examples. The couple SO_4F^-/HSO_4^- has a potential of 2.5 V *vs* 1.4 V for HSO_5^-/HSO_4^-.[65] In this example a fluorine atom replaces an hydroxyl residue. Substitution of phenyl with pentafluorophenyl at the ring carbon of oxaziridines[23,66] or introduction of fluorine atoms at the 8,8 position of camphoryl-*N*-sulfonyloxaziridine[23] make these compounds stronger oxidizers.

Perfluorinated oxaziridines are neutral, aprotic agents which may be vitally important characteristics for some transformations and are capable of tranferring oxygen to a variety of organic substrates. In most reported cases, substrates are hydrocarbons but epoxidation of some fluorinated and electron-deficient olefins such as chlorotrifluoroethylene and (trimethylsilyl)trifluoroethylene, can be also achieved by reaction with perfluoro-2,3-dialkyloxaziridine **5c**.[67]

Although some reports on the oxidative properties of perfluoro-2-methyl-,[45] perfluoro-2,3,3-trimethyl-,[14] and perfluoro-3,3-dimethyl-2-(alkylsulfonyl) oxaziridines[68] **2a**, **3**, and **10**, respectively, can be found in the literature, most papers describe reactions of perfluoro-2,3-dialkyloxaziridines **5**. The combination of physical properties and relatively simple preparation described in sections II and III, makes oxaziridines **5** reagents of choice for the reactions involving transfer of oxygen. Oxidations can be carried out in both aprotic and protic solvents. In most cases halogenated hydrocarbons (CFC-11, CFC-113, chloroform, methylene chloride) are employed, but other solvents namely *tert*-butyl alcohol and trifluoroethanol have also been used successfully. Usually, there is no noticable difference in the reactivity of perfluoro-2-*n*-butyl-3-*n*-propyl- and perfluoro-2-*n*-hexyl-3-*n*-pentyloxaziridines (**5c** and **5d**), except for the substrates with high steric demands. Steric hindrance at the reactive site of the substrate influences the ease of reaction for example oxidation of olefins, ethers. Electronic effects can also be very important

Scheme 12



for instance, in the site selectivity in epoxidation of alkenes.

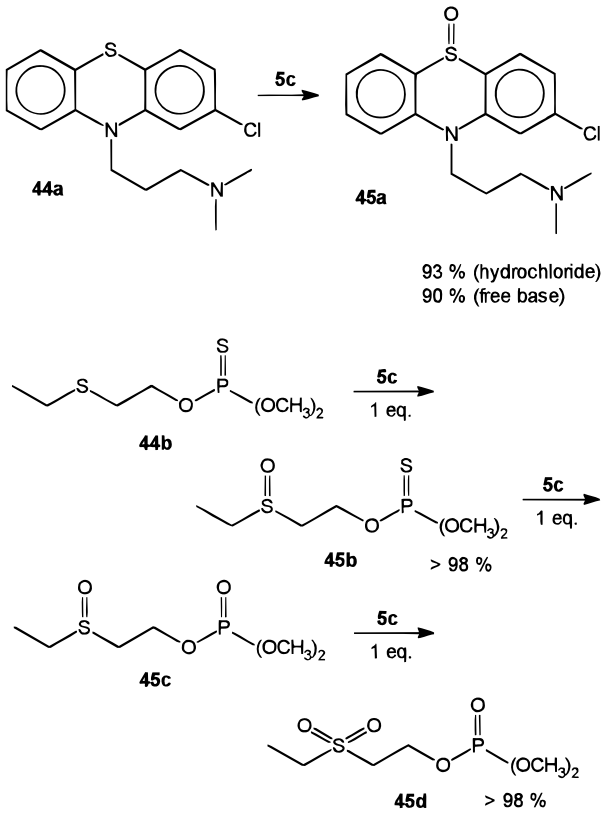
1. Organosulfur Substrates

Dialkyloxaziridines **5c**,**d** readily oxidize thioethers **41** to corresponding sulfoxides **42** in nearly quantitative yields when 1 equiv of the oxidizer is used and the reaction is performed at −40 °C.[69] Perfluorotrimethyloxaziridine **3** behaves similarly in the reaction with dimethyl sulfide.[14] The sulfones **43** can also be prepared starting either from sulfides **41** or sulfoxides **42** by employing 2 or 1 equiv of oxaziridine, respectively (Scheme 12). In both reactions sulfones are formed in high yields when the reaction is carried out at −20 to 0 °C. (*Z*)-Azaalkenes **4c**,**d** are the only coproducts formed in the reaction. The workup usually consists of removing the volatiles at reduced pressure.

Perfluoro-2-(sulfonylalkyl)-3,3-dimethyloxaziridines have also been used for the oxidation of sulfoxides.[68]

The oxidation of sulfides to sulfoxides has been explored with many different oxidizing agents; however, very few of these reagents are generally applicable. Many of these reagents are too reactive, overoxidizing sulfoxides to sulfones, particularly when the reagent is in excess. With other reagents, careful control of the reaction parameters is required or chemoselectivity is lost.[7] A quite interesting feature possessed by oxaziridines **5** is an unusual combination of high selectivity along with high oxidizing power. They are able selectively to convert sulfides into sulfoxides. The oxidation is carried out at −40 °C in inert solvent to control the heat of the reaction. The selectivity of the process is controlled by the sulfide to oxaziridine ratio and when equimolar amounts of reagents are used the sulfoxides isolated in 90−97% yield.[69] Corresponding sulfones are made by the reaction of sulfide with 2 mol of oxaziridine at slightly higher temperature. The oxidation of $C_6H_5SCH_3$ by **5c** (−20 to O °C, 15 min) [69] results in rapid formation of sulfone isolated in 95% yield in contrast to similar reaction of $C_6H_5SCH_3$ and 2-(phenylsulfonyl)-3-phenyloxaziridine leading to a mixture of sulfoxide and sulfone even aftre 20 h at room temperature.[7] The presence of various functional groups such as amide, azido, urea, phenol, ketone, carboxylic acid or ester, halogens, and even C=C bonds does not interfere with the oxidation of sulfur. Several trifluoromethyl-substituted vinyl sulfoxides which are not readily available by other methods were obtained in nearly quantitative yields by using oxaziridines **5c**,**d**.[70]

Scheme 13

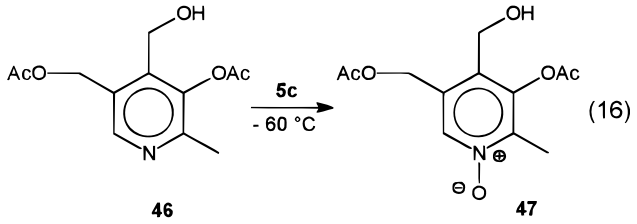


The sulfinyl and sulfonyl derivatives of some complex and bioactive sulfides have also been prepared in high yields. Tricyclic neuroleptic drugs such as chlorpromazine **44a** react as hydrochlorides and as free bases (Scheme 13). Oxidation of several organophosphorus agrochemicals containing the thioether function[71] yields either sulfoxides or sulfones. Phosphoric, phosphoramidic, and phosphorothioic moieties do not interfere with oxidations. In reaction of Demeton-*O*-methyl **44b**, the phosphorothionic function remains unaffected in the first step, formation of **45b**, but undergoes oxidative desulfurization, formation of **45c**, before oxidation of the sulfoxide.

2. Organonitrogen Substrates

In general, when pyridines **38** are treated with equimolar amounts of oxaziridines **5c**,**d** at −60 °C in a halogenated solvent, *N*-oxides **39** and *N*-imines **40** are formed in good yields (eq 15).[57,58] *Ortho*-substituted pyridines exclusively afford *N*-oxides while mixtures of *N*-oxide and *N*-imine are formed in oxidation of *meta*- and *para*-substituted pyridines. Formation of *N*-oxides **39** or *N*-imines **40** is the result of nucleophilic attack of pyridines **38** at oxygen or nitrogen of the oxaziridine ring, respectively. The regioselectivity of the reaction is controlled by steric bulk of the subsituent in pyridine ring and it is not sensitive to electronic factors. As noted in section IV.D, steric hindrance at reaction center makes the attack at nitrogen more difficult. Obviously, nitrogen is more hindered in the *ortho* substituted pyridines, which favors the formation of *N*-oxides.

Other reagents usually employed for preparation of *N*-oxides require either more drastic conditions[72] or have a limited shelf life.[73] The presence of some functional groups such as a C=C bond or an hydroxy group has no effect on the reaction, probably due to the particularly mild reaction conditions. For instance, pyridoxinediacetate **46** affords the corresponding *N*-oxide **47** in 84% isolated yields (eq 16).



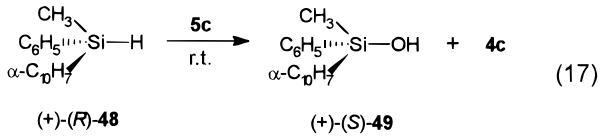
Corresponding *N*-oxides are formed exclusively or preferentially over *N*-imines in the oxidation of bi- and tricyclic heteroaromatic compounds, such as quinolines, acridines etc., by oxaziridines **5**.

2,3,3-Tris(trifluoromethyl)oxaziridine (**3**) was also reported to convert pyridine into *N*-oxide under mild conditions, but in low yield.[14]

3. Organosilicon Substrates

Oxidation of silanes to silanols requires neutral conditions because of possible rapid condensation of silanols with formation of siloxanes. Oxaziridine **5c** is effective in this reaction. Yields are nearly quantitative regardless the nature of the residues at silicon.[74] Geminal dioxyfunctionalization of R_2SiH_2 substrates can be achieved under proper conditions.

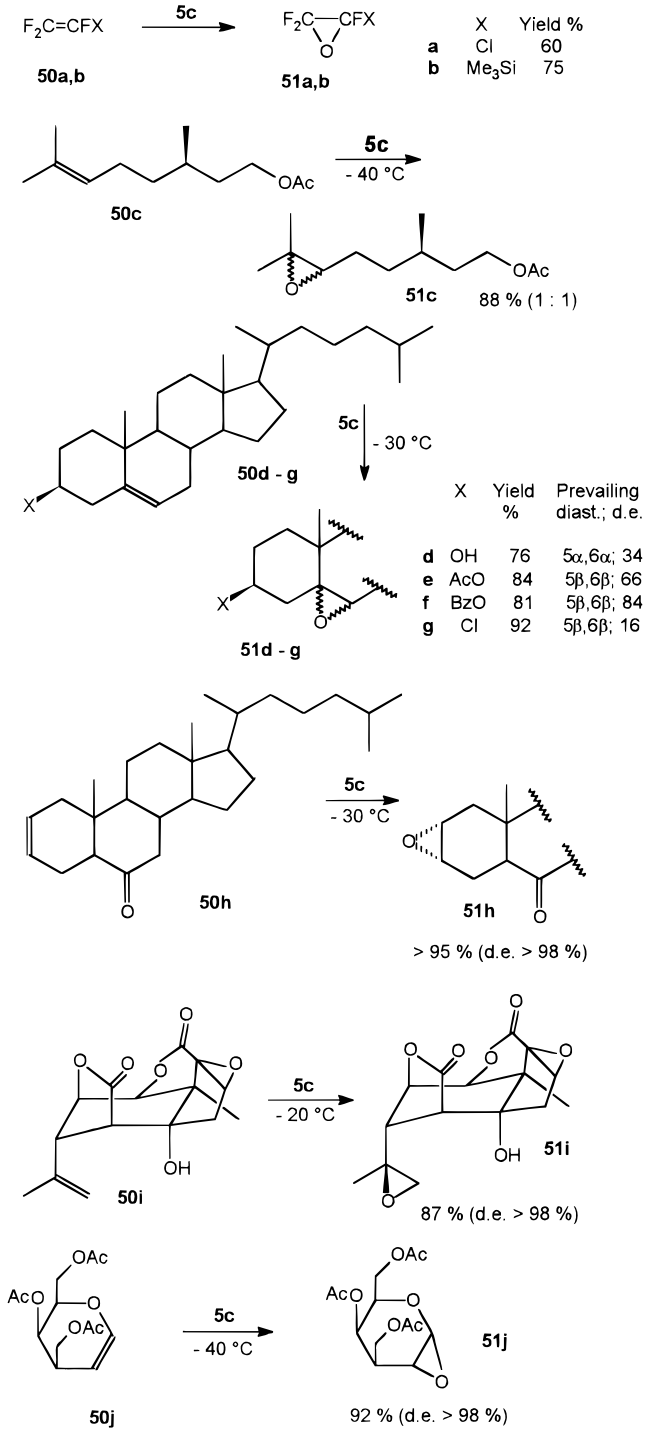
Reaction occurs nearly instantaneously at room temperature, but requires 1−2 h to go to completion at −78 °C. It is interesting that oxyfunctionalization of (+)-(*R*)-methylnaphtylphenylsilane (**48**) affords the corresponding silanol **49** having the (+)-(*S*) configuration. At room temperature in CFC-11 the reaction proceeds with complete retention of configuration (eq 17). However, when the reaction is performed at −78 or −20 °C the oxidation still occurs with retention of configuration, but with lower enantioselectivity.



4. Olefinic Double Bonds

Examples of the better oxidative properties of perfluorinated oxaziridines relative to their hydrocarbon analogues are that perfluoro-2-methyloxaziridine (**2a**),[45] 2,3,3-trimethyloxaziridine **3**,[14] and 2,3-dialkyloxaziridines **5c**,**d**[58,67] all rapidly perform the epoxidation of common olefins at low temperature (−10 to −50 °C) while *N*-sulfonyloxaziridines require prolonged heating for the same substrates.[7] The more deactivated the olefin substrate is; the more drastic the reaction conditions are. Several hours at ambient temperature are required to epoxidize methyl cinnamate by oxaziridine **5c**, while the more electron-deficient chlorotrifluoroethylene **50a** only can be converted into corresponding epoxide **51a** at 100 °C (Scheme 14). The epoxidation reaction occurs with retention of configuration of the substrate, i.e. *trans* olefins afford *trans* epoxides. (*Z*)-Azaalkenes

Scheme 14

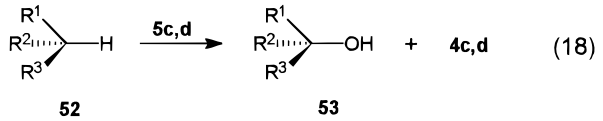


4c,**d** are formed exclusively from the oxidizing agent. The diastereoselectivity of process with chiral substrates can vary depending on the oxaziridine (**5c** or **5d**) and the solvent. The example of (*R*)-citronellol acetate **50c** shows that if the chiral center is far away from the double bond and there is conformational freedom in the molecule no diastereoselectivity is observed (Scheme 14). The different diastereoselectivities observed for cholesterol derivatives **50d**−**g** prove how the behavior of **5c** can be sensitive to subtle stereoelectronic effects. Cholestenone **50h** reveals how complete stereocontrol can be reached when the convenient constraints are present. One single diastereoisomer is obtained also in the epoxidation of picrotoxinin **50i** while MCPBA affords a 5:2 mixture of products.[75] Configuration of **51h**,**i** can be predicted, assuming that the oxaziridine approaches from the least hindered face of the alkene and the complete face selectivity obtained on **50i** reveals how epoxidation using perfluorinated oxaziridines is more sensitive to steric effects than with peracids.

Epoxidation of glycals with oxaziridines **5c**,**d** to give 1,2-anhydrosugars has been studied.[76] The reaction of tri-*O*-acetyl-D-galactal **50j** is shown in Scheme 14. The process occurs under particularly mild conditions for an electron-rich double bond. Good yields are obtained despite the fact that 1,2-anhydrosugars are highly labile. These reactions also give further insights into the factors affecting diastereoselectivity of the epoxidation. Temperature has no effect while solvent can dramatically change diastereoisomeric ratio of products.

5. Unactivated Hydrocarbons

2,3-Dialkyloxaziridines **5c**,**d** react with unactivated hydrocarbons **52** at room temperature and in the condensed phase to give oxyfunctionalization products **53** and (*Z*)-azaalkenes **4c**,**d** (eq 18).[77] The



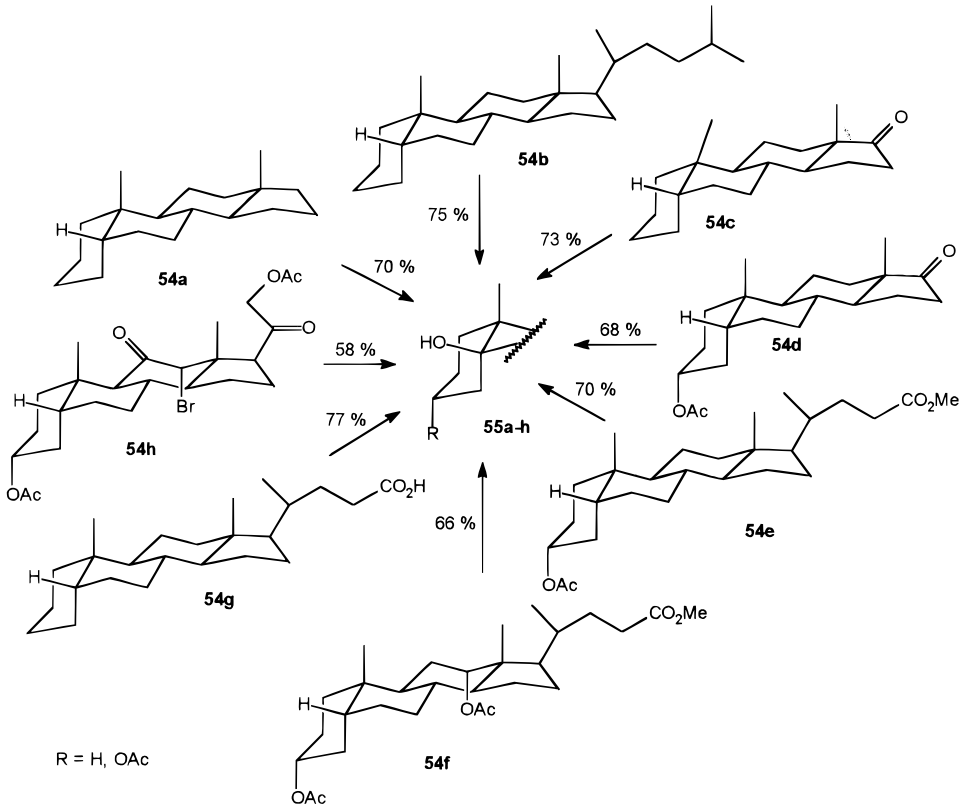
(18)

reaction occurs with high siteselectivity, regioselectivity, and diasteroselectivity. A remarkable selectivity for tertiary C−H bond is observed in most cases. Oxidation of C−H bond in methyl group or dioxyfunctionalization of the substrate having several oxidizable sites have never been observed. Minor amounts of ketones are formed, probably through further oxidation of initially produced secondary alcohols and the amount of these by products increases with longer reaction times. Alicyclic hydrocarbons carrying equatorial tertiary C−H bonds react faster than isomers having axial C−H bonds, for instance oxidation of *cis*-dimethylcyclohexane and *cis*-decalin is faster than the reaction of corresponding *trans* isomers. Oxidation occurs with retention of configuration (>98%).

Only very few reagents can perform the selective oxyfunctionalization of unactivated hydrocarbon sites. A common characteristic of most of them for example, ozone, peracids, hydrogen peroxide, dioxiranes, etc., is their intrinsic instability which is related to the looseness of the bond between the electrophilic oxygen, delivered in the oxidation process, and the rest of the oxidizing agent. For this reason, they decompose spontaneously at room temperature liberating oxygen. Remembering that oxaziridines **5** are indefinitely stable at room temperature and decompose only at 120−160 °C without oxygen loss, their ability to work as effective oxyfunctionalizing agents is quite surprising.

The reactivity and the stereospecificity of oxaziridines **5** in oxyfunctionalization reactions are similar to those of dioxiranes, and the similarity might be extended to the mechanistic aspect. An "oxenoid" O-atom insertion into C−H bonds has been traditionally proposed for these oxidizers,[78] but some data

Scheme 15



supporting a radical mechanism have been recently reported.[79]

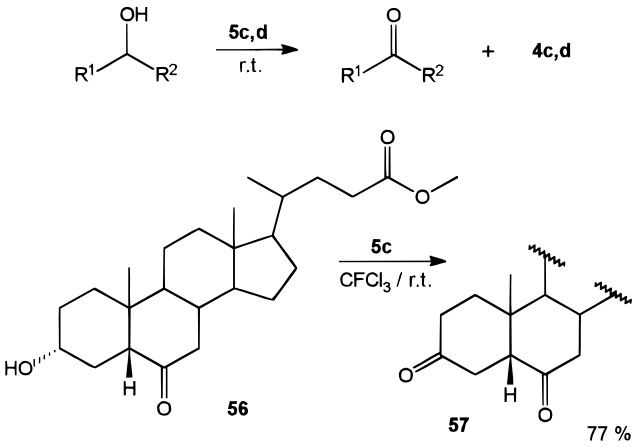
The oxyfunctionalization reaction is not limited to simple molecules, but extends to complex, polyfunctional substrates of biological interest which are a severe test of selecivity of the oxygenation reaction. In reactions of several 5β-steroids **54** with the oxaziridine **5c**, the corresponding 5β-hydroxy derivatives **55** are isolated in good yields. More importantly, complete siteselectivity and stereoselectivity is observed in all these reactions (Scheme 15).[80]

The reaction has been performed with androstanes, cholestanes, pregnanes, and cholanic acids as substates. 5β-Hydrogen is always abstracted in preference to the others in the substrate. Selectivities in this process can sometimes be better than reported for dioxiranes.[81] The preferential oxidation at C-5, compared to the other steroidal tertiary carbon atoms, C-8, C-9, C-14, C-17, C-20, and C-25, is probably strictly related to the *cis* junction of the A/B rings of steroids **54**, but further studies are required before the relative relevance of steric and electronic effects can be assessed. Halide, ketone, carboxylic acid, and ester moieties can be present on different sites of the steroid framework without the course of the reaction being changed. The only observed effect is an increase of reaction times when the functional group is near the reactive site. For example 2, 2, and 20 h are needed for **54a**, **54c**, and **54d**, respectively. The same effect is observed when dioxiranes are used.[82] This can be an argument favoring of the electrophilic nature of oxaziridines **5**.

6. Alcohols and Ethers

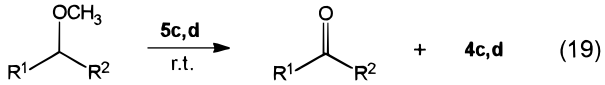
Oxaziridines **5c,d** oxidize secondary alcohols to corresponding ketones at room temperature.[83] (*Z*)-

Scheme 16



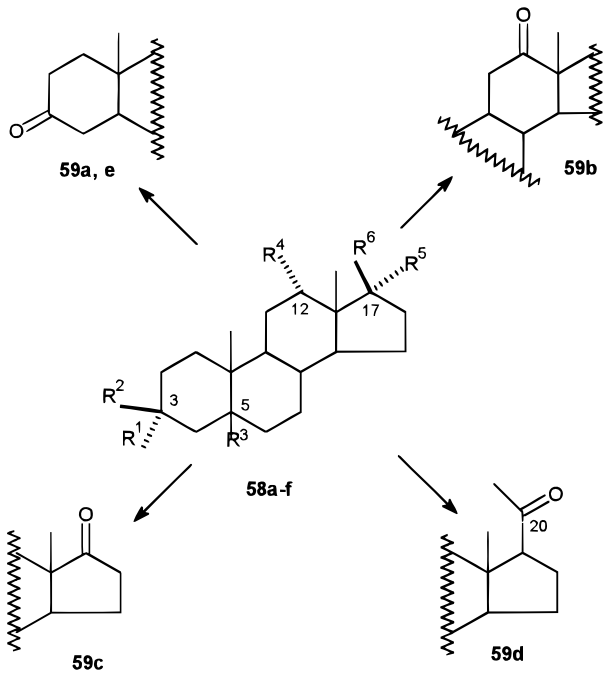
Perfluoroimine **4c**,**d** are formed as byproducts (Scheme 16). Both oxaziridines **5c** and **5d** behave similarly. The presence of a phenyl or a carbethoxy group in the substrate does not interfere with the oxidation. The same is true for tertiary alcohols or bulky substituents. Some steroids are oxidized in high yields, for instance 6-ketolithocholic acid methyl ester **56** affords the 3,6-diketo product **57** in 77% yield. Epimerization at C-5 to give 5α-cholanic products, which can take place through enolization of the keto group at C-6, is not observed due to the neutral conditions of the reaction.

Interestingly, methyl ethers of secondary alcohols are also oxidized to corresponding carbonyl products. Azaalkenes **4** are formed as coproducts (eq 19).[84] The



(19)

Scheme 17



	R^1	R^2	R^3	R^4	R^5	R^6	Isolated Yields (%)
58a	OCH_3	H	αH	H		O	84
b	O		αH	H	H	OCH_3	91
c	OAc	H	βH	OCH_3	H	$CH(CH_3)CH_2CH_2CO_2CH_3$	76
d	H	OAc	αH	H	H	$CH(CH_3)βOCH_3$	79
e	H	OCH_3	αH	H	H	$CH(CH_3)βOCH_3$	82

mechanism of this process can be rationalized through formation of hemiketal, spontaneously producing the ketone by loss of a molecule of methanol. The reaction is highly selective with tertiary C−H bond being oxidized exclusively.

The oxidation of alkyl ethers of secondary alcohols $R^1R^2CHOCH_2R$ is much less selective and leads to a mixture of products.

Steroids **59** with a keto group on C-3, C-12, C-17, and C-20 can be obtained starting from the corresponding methoxy precursors **58**, having an androstane, pregnane, and cholanic acid skeleton and belonging to either the 5α or the 5β series (Scheme 17). Depending on the site to be oxidized, quite different reaction conditions are required to perform the reaction. Oxidation of ethers, as epoxidation of alkenes,[85] is sensitive to steric hinderance in the substrate. A synthetically useful exploitation of this effect is the selective oxidation of only one methoxy group in dimethoxylated compound **59e**. The attack at the more hindered and less favored site can nevertheless be realized by changing the ether functionality at the preferential oxidation site to an ester (compound **59d**).

V. Conclusions

While investigations on the synthesis and the reactions of polyfluorinated oxaziridines are still in their initial stages, sufficient work has been completed to show their usefulness in fine organic synthesis. It has been demonstrated, for instance, that these stable oxidizing agents have a unique reactivity profile. Fluorinated oxaziridines are neutral, aprotic oxidizers, and they are able to transfer oxygen to a wide variety of substrates including olefins, silanes, amines, alcohols, ethers, etc. Surprisingly, these powerful oxidizing agents are quite selective, for example they are able to convert sulfides into sulfoxides practically without over oxidation. A high sensitivity of fluorooxaziridines to a steric hindrance in a substrate is another "tool" which can be used for selective transformations of hydrocabons. The price of starting materials and a limited accessibility of fluorinated oxaziridines are at present the only two factors which can limit the use of these compound as oxygen-transfer reagents. The situation might change by development of new and less costly methods for the synthesis of perfluorinated oxaziridines.

We hope that this review will stimulate the further interest in the use of fluorinated oxaziridines in fine organic synthesis.

VI. Acknowledgments

Authors thank Prof. Darryl D. DesMarteau for stimulating discussions, Boris Vekker, Dr. R. Thomas Baker, and Dr. Carl G. Krespan for help in the preparation of manuscript, and reviewers 65 and 67 for a number of valuable comments and suggestions.

VII. References

(1) (1) Krimm, H. British Patent 743,940, 1953; *Chem. Abstr.* **1957**, v 265.
(2) Emmons, W. D. *J. Am. Chem. Soc.* **1956**, *78*, 608.
(3) Horner, L.; Jurgens, E. *Chem. Ber.* **1957**, *90*, 2184.
(4) Falardeau, E. R.; DesMarteau, D. D. *J. Am. Chem. Soc.* **1976**, *98*, 3529.
(5) Schmitz, E. *Adv. Heterocycl. Chem.* **1963**, *2*, 83
(6) Schmitz, E. *Adv. Heterocycl. Chem.* **1979**, *24*, 63
(7) Davis, F. A.; Sheppard, A. C. *Tetrahedron* **1989**, *45*, 5703.
(8) Katritzky, A. R.; Rees, C. W. *Comprehensive Heterocyclic Chemistry*; Vol. 7, Chapter 5, p 204.
(9) Davis, F. A.; Thimma Reddy, R.; Han, W.; Reddy, R., E. *Pure Appl. Chem.* **1993**, *65*, 633.
(10) Davis, F. A.; Chen, B.-C. *Chem. Rev.* **1992**, *92*, 919.
(11) Sekiya, A.; DesMarteau, D. D. *Inorg. Chem.* **1979**, *18*, 919.
(12) Sekiya, A.; DesMarteau, D. D. *Inorg. Chem.* **1980**, *19*, 1330.
(13) Zheng, Y. Y.; DesMarteau, D. D. *J. Org. Chem.* **1983**, *48*, 4844.
(14) Bragante, L.; DesMarteau, D. D. *J. Fluorine Chem.* **1991**, *53*, 181.
(15) Petrov, V. A.; DesMarteau, D. D. *Mendeleev Commun.* **1993**, 87.
(16) Petrov, V. A.; DesMarteau, D. D. *Inorg. Chem.* **1992**, *131*, 3776.
(17) Navarrini, W.; DesMarteau, D. D. U. S. Pat. 4,874,875, 1989; *Chem. Abstr.* **1990**, *112*, 159140y.
(18) Knunyants, I. L.; Gontar', A. F. *Sov. Sci. Rev. Sec. B.* **1984**, *5*, 219 and references cited therein.
(19) Ratcliffe, C. T. U.S. Pat. 4,287,128, 1981; *Chem. Abstr.* **1982**, *96*, 6550h.
(20) De Kimpe, N.; De Corte, B. *Tetrahedron* **1992**, *48*, 7345.
(21) Petrov, V. A.; Mlsna, T. E.; DesMarteau, D. D. *J. Fluorine Chem.* **1994**, *68*, 277.
(22) Davis, F. A.; McCauley, J. P., Jr.; Chattopadhyay, S.; Harakal, M. E.; Towson, J. C.; Watson, W. H.; Tavanaiepour, I. *J. Am. Chem. Soc.* **1987**, *109*, 3370. Davis, F. A.; Chattopadhyay, S. *Tetrahedron Lett.* **1986**, *27*, 5079. Davis, F. A.; Chattopadhyay, S.; Towson, J. C.; Lal, S.; Reddy, T. *J. Org. Chem.* **1988**, *53*, 2087.
(23) Davis, F. A.; Weismiller, M. C.; Murphy, C. K.; Thimma Reddy, R.; Chen, B.-C. *J. Org. Chem.* **1992**, *57*, 7274.
(24) Petrov, V. A.; DesMarteau, D. D. *J. Org. Chem.* **1993**, *58*, 4754.
(25) Petrov, V. A.; DesMarteau, D. D. *J. Fluorine Chem.* **1996**, in press.
(26) Mlsna, T. E.; Young, J. A.; DesMarteau, D. D., manuscript in preparation.

(27) Gontar', A. F.; Glotov, E. N.; Rubachev, A. A.; Knunyants, I. L. *Izv. Akad. Nauk SSSR, Ser. Khim.* **1984**, 1874; *Chem. Abstr.* **1985**, *102*, 148678.
(28) Petrov, V. A.; Belen'kii, G. G.; German L. S. *Izv. Akad. Nauk SSSR, Ser. Khim.* **1985**, 1934; *Chem. Abstr.* **1986**, *105*, 78461.
(29) Petrov, V. A.; Kunanets, V. K.; Makarov, K. N.; German, L. S. *Izv. Akad. Nauk SSSR, Ser. Khim.* **1989**, 646; *Chem. Abstr.* **1990**, *112*, 7060.
(30) Petrov, V. A.; Grinevskaya, V. K.; Makarov, K. N.; Mysov, E. I.; Galakhov, M. V.; German, L. S. *Izv. Akad. Nauk SSSR, Ser. Khim.* **1990**, 1616; *Chem. Abstr.* **1990**, *113*, 231191.
(31) Petrov, V. A.; DesMarteau, D. D. *Inorg. Chem.* **1992**, *31*, 3776.
(32) Hynes, J. B.; Bishop, B. C.; Bondypadhuay, P.; Biegelow, B. *J. Am. Chem. Soc.* **1963**, *85*, 83
(33) Hund, H.; Roeschenthaler, G. V. *Phosphorus, Sulfur Silicon Relat. Elem.* **1993**, *75*, 209; *Chem. Abstr.* **1994**, *120*, 191816z.
(34) Del'tsova, D. P.; Gambaryan, N. P. Lur'e, E. P. *Izv. Akad. Nauk SSSR, Ser. Khim.* **1979**, 1788; *Chem. Abstr.* **1980**, *92*, 6475e.
(35) Banks, R. E.; Du Boisson, R. A.; Marracini, A.; Sekhri, L.; Tipping, A. E. *J. Fluorine Chem.* **1987**, *37*, 295.
(36) Petrenko, N. I.; Gerasimova, T. N. *Zh. Org. Khim.* **1986**, *22*, 231; *Chem. Abstr.* **1987**, *106*, 4913e.
(37) Petrenko, N. I.; Shelkovnikov, V. U.; Eroshin, V. I.; Gerasimova, T. N. *J. Fluorine Chem.* **1987**, *36*, 99.
(38) Jennings, W. B.; Watson, J. A.; Tolley, M. S. *J. Am. Chem. Soc.* **1987**, *109*, 8099 and references herein.
(39) Montanari, F.; Morreti, I.; Torre, G. *Gazz. Chim. Ital.* **1973**, *103*, 681.
(40) Bjorgo, J.; Boyd, D. R. *J. Chem. Soc., Perkin Trans. 2* **1973**, 1575.
(41) Kostyanovsky, R. G.; Rudchenko, V. F.; Shtamburg, V. G.; Chervin, I. I.; Nasibov, S. S. *Tetrahedron* **1981**, *37*, 4245.
(42) Jennings, W. B.; Watson, S. P.; Boyd, D. R. *J. Chem. Soc., Chem. Commun.* **1988**, 931.
(43) Petrov, V. A.; DesMarteau, D. D. *J. Chem. Soc., Perkin Trans. 1* **1993**, 505.
(44) Lam, W. Y.; DesMarteau, D. D. *J. Am. Chem. Soc.* **1982**, *104*, 4034.
(45) O'Brien, B. A.; Lam, W. Y.; DesMarteau, D. D. *J. Org. Chem.* **1986**, *51*, 4466.
(46) Navarrini, W.; DesMarteau, D. D. U.S. Patent 5,196,595, 1993; Eur. Pat. Appl. EP 347,885; *Chem. Abstr.* **1990**, *113*, 6317g.
(47) Di Ruocco, V.; Garbassi, F. Eur. Pat. Appl. EP 511,635; *Chem. Abstr.* **1993**, *118*, 235488J.
(48) Christensen, D.; Jorgensen, K. A.; Hazel, R. G. *J. Chem. Soc., Perkin Trans. 1* **1990**, 2391.
(49) Andreae, S.; Schmitz, E. *Synthesis* **1991**, 327.
(50) Boyd, D. R.; Jennings, W. D.; McGuckin, R. M.; Rutherford, M.; Saket, B. M. *J. Chem. Soc., Chem. Commun.* **1985**, 582.
(51) Hanquet, G.; Lusinchi, X. *Tetrahedron Lett.* **1993**, *34*, 5299.
(52) Hanquet, G.; Lusinchi, X.; Milliet, P. *Tetrahedron Lett.* **1988**, *29*, 3941.
(53) Navarrini, W.; DesMarteau, D. D. U.S. Patent 4,948,903; Eur. Pat. Appl. EP 347,885, 1989; *Chem. Abstr.* **1990**, *113*, 6317g.
(54) Fokin, A. V.; Uzun, A. T.; Stolyarov, V. P. *Usp. Khim.* **1977**, *46*, 1995.
(55) Sekiya, A.; DesMarteau, D. D. *J. Org. Chem.* **1979**, *44*, 1131.
(56) Sekiya, A.; DesMarteau, D. D. *J. Fluorine Chem.* **1979**, *14*, 289.
(57) Balsarini, C.; Novo, B.; Resnati, G. *J. Fluorine Chem.*, in press.
(58) Bernardi, R.; Novo, B.; Resnati, G. *J. Chem. Soc., Perkin Trans. 1*, in press.
(59) Adam, W.; Curci, R.; Edwards J. O. *Acc. Chem. Res.* **1989**, *22*, 205.
(60) Murray, R. W. *Chem. Rev.* **1989**, *89*, 1187.
(61) Butler, A.; Clague, M. J.; Meister, G. E. *Chem. Rev.* **1994**, *94*, 625.
(62) Conte, V.; Di Furia, F.; Modena, G. In *The Chemistry of Functional Groups, Organic Peroxides*; Ando, W., Ed.; John Wiley & Sons: Chischester, 1992; pp 559−598.
(63) Sharpless, K. B.; Johnson, R. A. In *Comprehensive Organic Synthesis*; Trost, B. M., Fleming, I., Eds.; Pergamon Press: Oxford, 1991; pp 389−436.
(64) (a) Partch, R. E. *J. Am. Chem. Soc.* **1967**, *89*, 3662. (b) Kochi, J. K.; Tang, R. T.; Bernath, T. *J. Am. Chem. Soc.* **1973**, *95*, 7114. (c) McKillop, A.; Fowler, J. S.; Zelesko, M. J.; Hunt, J. D.; Taylor, E. C.; McGillivray, G. *Tetrahedron Lett.* **1969**, 2423. (d) Brown, H. C.; Wirkkala, R. A. *J. Am. Chem. Soc.* **1966**, *88*, 1447. (e) Radhakrishna, A. S.; Parham, M. E.; Riggs, R. M.; Loudon, G. M. *J. Org. Chem.* **1979**, *44*, 1746. Varvoglis, A. *Synthesis* **1984**, 709. Spyroudis, S.; Varvoglis, A. *Synthesis* **1975**, 445. (f) Gallos, J.; Varvoglis, A. *J. Chem. Res.* (*M*) **1982**, 1649; (*S*) 150. (g) Ellis, P. E.; Lyons, J. E. M. *J. Chem. Soc., Chem. Commun.* **1989**, 1315. Ogoshi, i.; Suzuki, Y.; Kuroda, Y. *Chem. Lett.* **1991**, 1547. Ellis, P. E.; Lyons, J. E. *J. Chem. Soc., Chem. Commun.* **1989**, 1189. (h) Mello, R.; Fiorentino, M.; Sciacovello, O.; Curci, R. *J. Org. Chem.* **1988**, *53*, 3890.
(65) Appelman, E. H.; Basile, L. J.; Hayatsu, R. *Tetrahedron* **1984**, *40*, 189.
(66) Kennedy, R. J.; Stock, A. M. *J. Org. Chem.* **1960**, *25*, 1901.
(67) Petrov, V. A.; Resnati, G.; Montanari, V.; DesMarteau, D. D. *Proceedings of the XIIIth International Symposium on Fluorine Chemistry*; Bochum, FGR, Sept 1 - 6, 1991. In *J. Fluorine Chem.* **1991**, *54*, 399.
(68) Petrov, V. A.; Mlsna, T.; DesMarteau, D. D. 11th Winter Fluorine Conference, St. Petersburg, 22−27 January 1993.
(69) DesMarteau, D. D.; Petrov, V. A.; Montanari, V.; Pregnolato, M.; Resnati, G. *J. Org. Chem.* **1994**, *59*, 2762.
(70) Novo, B.; Resnati, G.; Bégué, J.-P.; M'Bida, A.; Bonnet-Delpon, D. *Synthesis*, in press.
(71) Terreni, M.; Pregnolato, M.; Resnati, G.; Benfenati, E. *Tetrahedron*, **1995**, *51*, 7981.
(72) Abramovitch, R. A.; Smith, E. M. In *The Chemistry of Heterocyclic Compounds, Pyridine and its Derivatives*; Abramovitch, R. A., Ed.; John Wiley & Sons: New York, 1974; Supplement 2, pp 3−24. Ohta, A.; Ohta, M. *Synthesis* **1985**, 216.
(73) Gallopo, A. R.; Edwards, J. O. *J. Org. Chem.* **1981**, *46*, 1684. Murray, R. W.; Jeyaraman, R. *J. Org. Chem.* **1985**, *50*, 2847.
(74) Cavicchioli, M.; Montanari, V.; Resnati, G. *Tetrahedron Lett.* **1994**, *35*, 6329.
(75) Miyashita, M.; Suzuki, T.; Yoshikoshi, A. *J. Am. Chem. Soc.* **1989**, *111*, 3728.
(76) Cavicchioli, M.; Mele A.; Montanari, V.; Resnati, G. *J. Chem. Soc., Chem. Commun.* **1995**, 901.
(77) DesMarteau, D. D.; Donadelli, A.; Montanari, V.; Petrov, V. A.; Resnati, G. *J. Am. Chem. Soc.* **1993**, *115*, 4897.
(78) Mello, R.; Fiorentino, M.; Fusco, C.; Curci, R. *J. Am. Chem. Soc.* **1989**, *111*, 6749. Hamilton, G. A. In *Molecular Mechanisms of Oxygen Activation*, Hayashi, O., Ed.; Academic Press: New York, 1974; Chapter 10.
(79) Minisci, F.; Zhao, L.; Fontana, F.; Bravo, A. *Tetrahedron Lett.* **1995**, *36*, 1895. Minisci, F.; Zhao, L.; Fontana, F.; Bravo, A. *Tetrahedron Lett.* **1995**, *36*, 1697. Bravo, A.; Fontana, F.; Fronza, G.; Mele, A.; Minisci, F. *J. Chem. Soc., Chem. Commun.* **1995**, 1573.
(80) Arnone A.; Cavicchioli, M.; Montanari, V.; Resnati, G. *J. Org. Chem.* **1994**, *59*, 5511.
(81) Bovicelli, P.; Gambacorta, A.; Lupattelli, P. *Tetrahedron Lett.* **1992**, *33*, 7411.
(82) Dixon, J. T.; Holzapfel, W. C.; van Heerden, F. R. *Synth. Commun.* **1993**, *23*, 135. Bovicelli, P.; Lupattelli, P.; Fiorini, V. *Tetrahedron Lett.* **1993**, *34*, 6103.
(83) DesMarteau, D. D.; Petrov, V. A.; Montanari, V.; Pregnolato, M.; Resnati, G. *Tetrahedron Lett.* **1992**, *33*, 7245.
(84) Arnone A.; Bernardi, R.; Cavicchioli, M.; Resnati, G. *J. Org. Chem.* **1995**, *60*, 2314.
(85) Davis, F. A.; Towson, J. C.; Vashi, D. B.; Thimma Reddy, R.; McCauley, J. P., Jr.; Harakal, M. E.; Gosciniak, D. J. *J. Org. Chem.* **1990**, *55*, 1254.

CR941146H