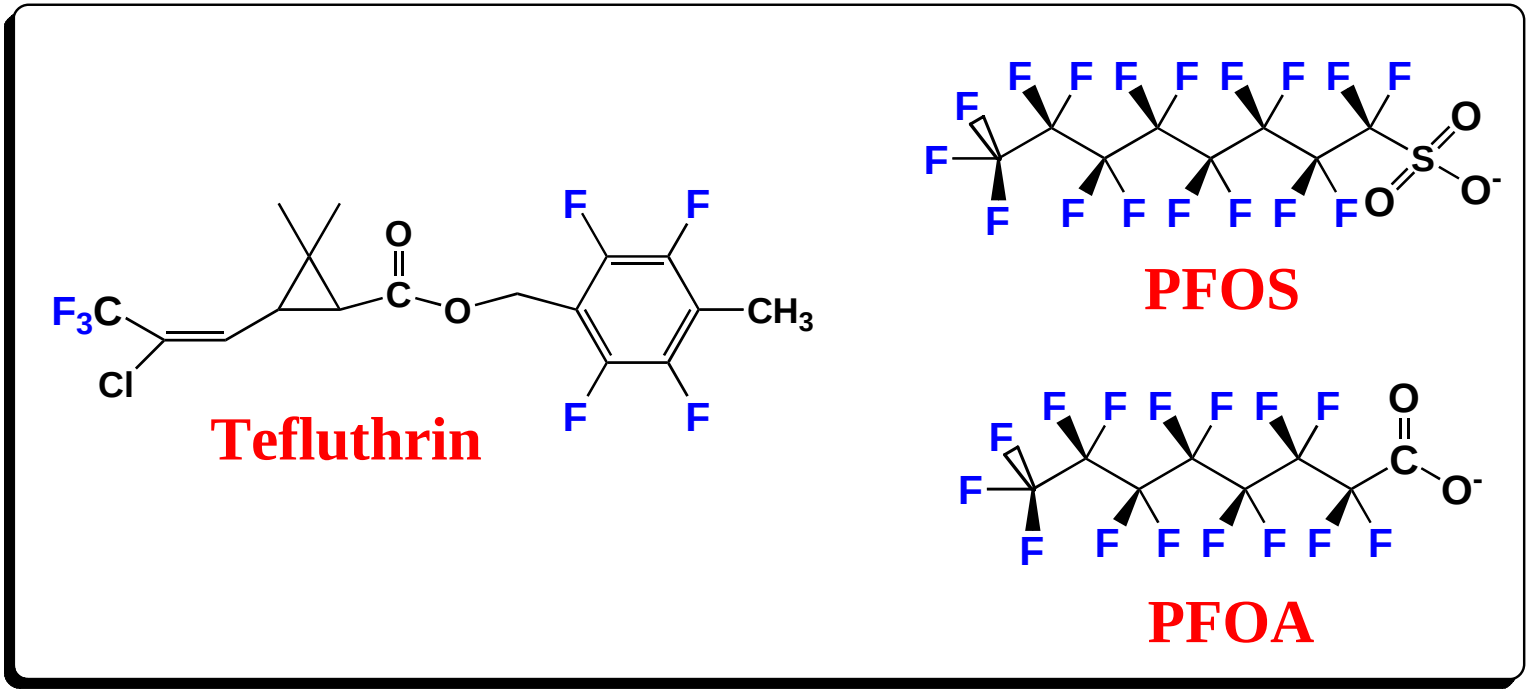
"Chemical Personality of Fluorinated Organics or *Why Chemical Architecture Matters!"*



Scott Mabury *et al*

Department of Chemistry

University of Toronto

Fluoros August, 2005

Items in Talk ~

- **“Natural” Organofluorines**
- **Pesticides, Pharmaceuticals, Consumer, Industrial materials**
- **Fluorine and the C-F bond**
- **Reactivity ~ oxidation, photolysis, hydrolysis, elimination, metabolism**
- **Physical Properties…water solubility, partitioning, volatility**
- **Summary with ‘big picture’ on PFOS and PFOA**

Natural Organic Fluorines?

Organofluorines =~30; Cl=2,400; Br=2,050

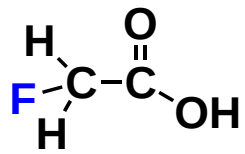
Haloperoxidase?

$F^- \rightleftharpoons F_2 + 2e \quad (E^0 = -3.06V)$

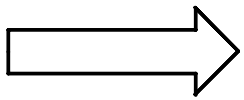
$H_2O_2 + 2H^+ \; 2e \rightleftharpoons 2H_2O \quad (E^0 = +1.71V)$

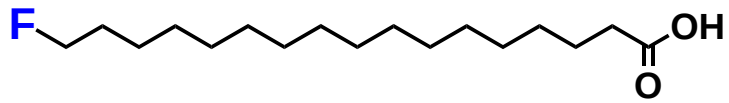
[Cl^- E^0=-1.36V; Br^- E^0=-1.07]

Most Common



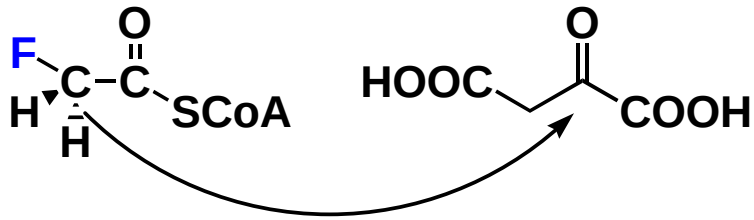
'Fluoroacetate"



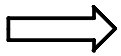


Oleic, stearic, palmitic, mystic, etc

Highly Toxic

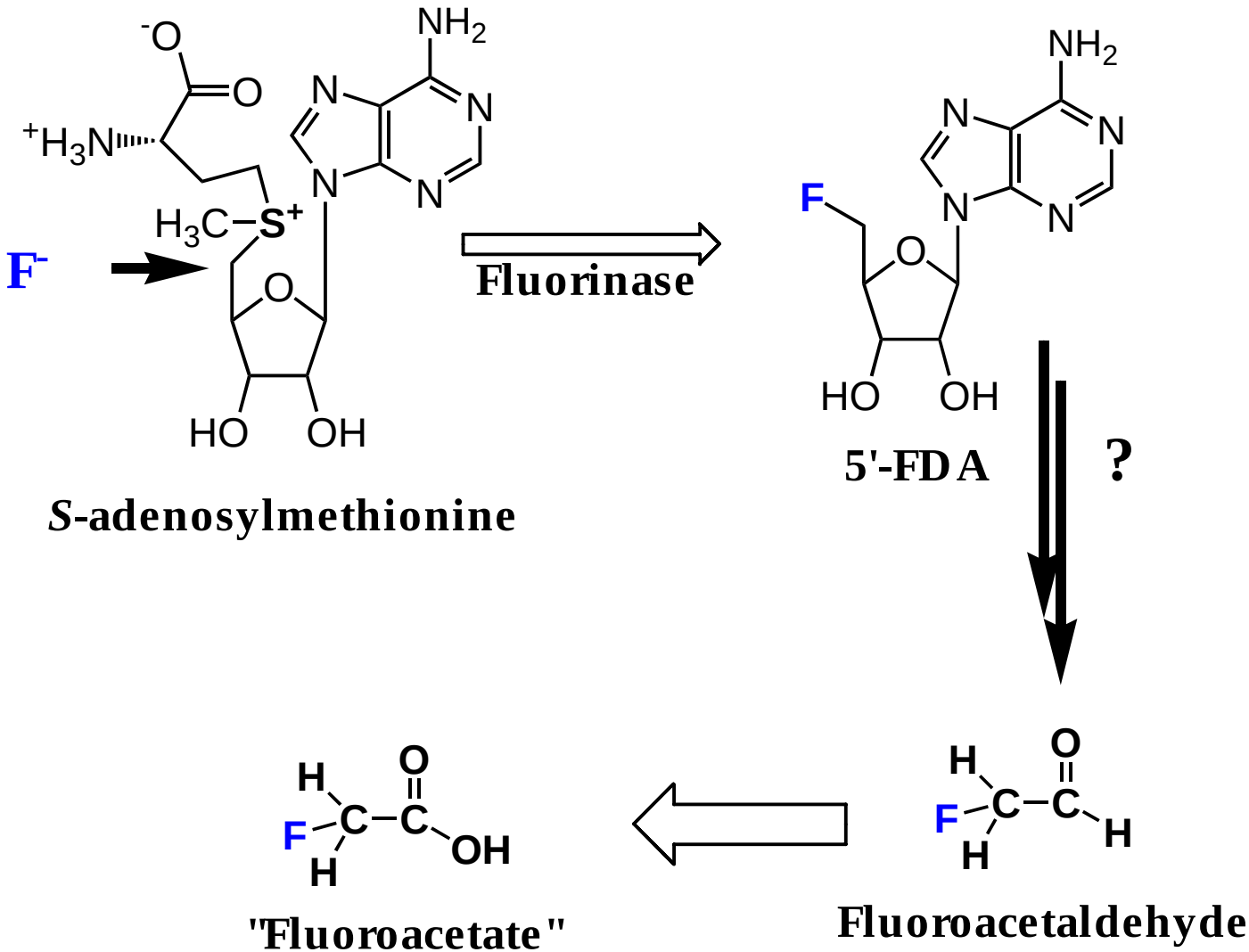


'Fluorocitrate'



inhibits citrate transport

Biosynthesis of Fluoroacetate



O'Hagan et al, 2002, *Nature*, 416, p279.

"Small Polyfluorinated Organics"

Anthropogenic 'small organofluorines'

Aluminum Production: CF_4 (82), CF_3CF_3 (3) [0.75 and 0.11 kg/ton of Al]
Freons: $CFCl_3$ (267), CF_2Cl_2 (535), $CF_2ClCFCl_2$ (85)
HCFC: CF_3CFH_2 (12), CHF_2Cl (145), CH_3CF_2Cl (15)
HFCs: CF_3CHFCF_3, $CF_3CHFCHFCF_2CF_3$, $CH_2FCF_2CHF_2$

Note: numbers in (x) reflect atmospheric concentration pptv;

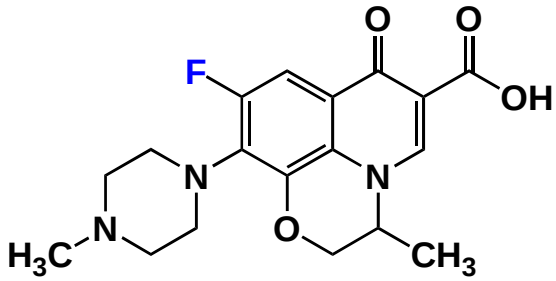
IPCC Climate Change 2001: The Scientific Basis

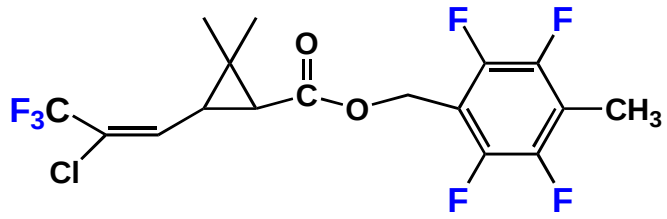
Natural Sources as well?

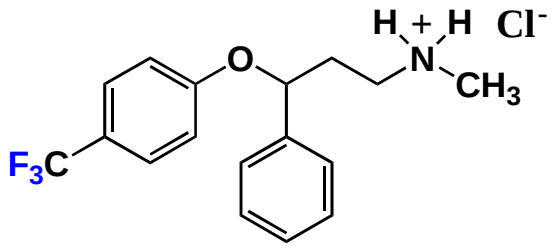
CF_4, CF_2Cl_2, $CFCl_3$, CF_3Cl, CHF_3, $CF_2=CF_2$ (fluorite)[1]....
$CFCl_3$, CF_2Cl_2, $CF_2=CF_2$, CHF_2Cl, $CHFCl_2$, CCl_2FCClF_2 (volcanoes)[2]...
CF_3COOH ....estimate of 268 million tons in the world's oceans[3]; (ocean vents[4])

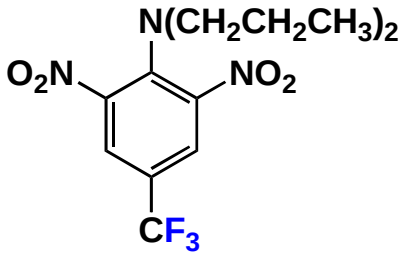
1) Harnisch & Eisenhauer, 1998; Harnischs et al, 2000.
2) Isidorov et al 1990; Isidorov, 1990.
3) Frank et al, 2002
4) Scott et al, 2005

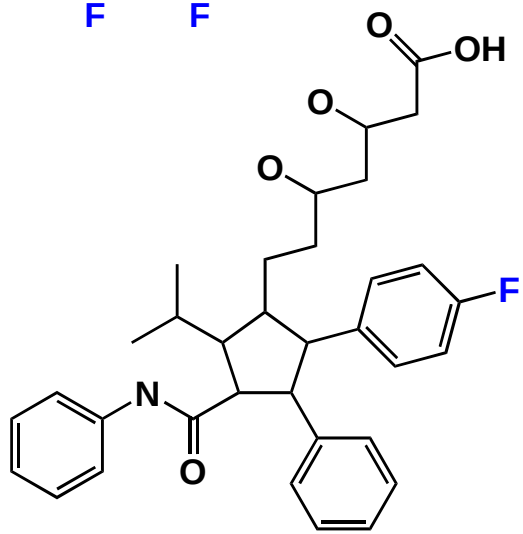
Pesticides and Pharmaceuticals…

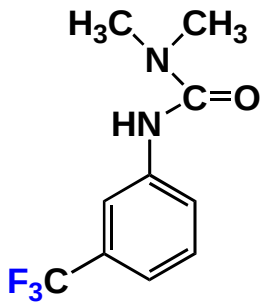


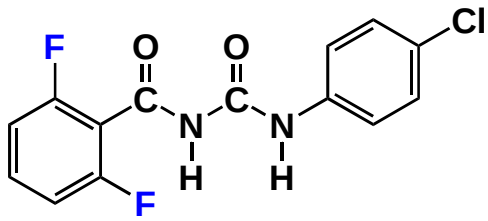


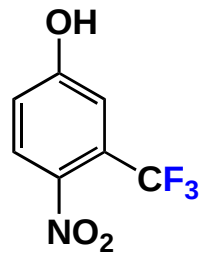




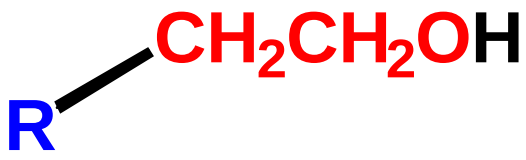








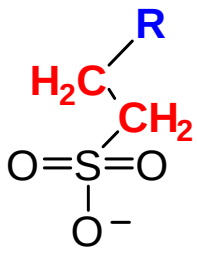
Polyfluorinated long alkyl chain materials...



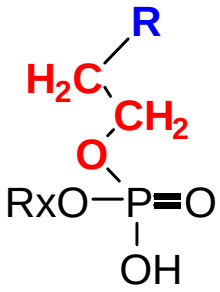
R= $CF_2CF_2CF_2CF_2CF_2CF_2CF_2CF_3$

$N(CH_3)SO_2CF_2CF_2CF_2CF_2CF_2CF_2CF_2CF_3$

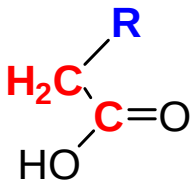
Some Linkages...



Sulfonates (via sulfide)

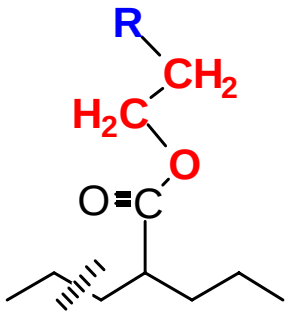


Phosphates

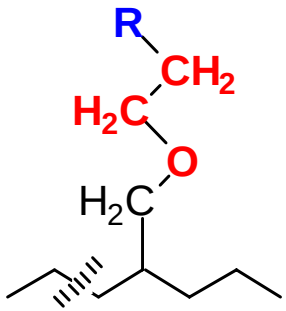


Carboxylates

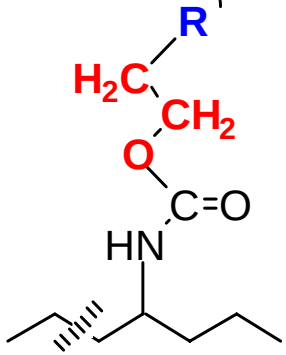
in Polymers



Ester

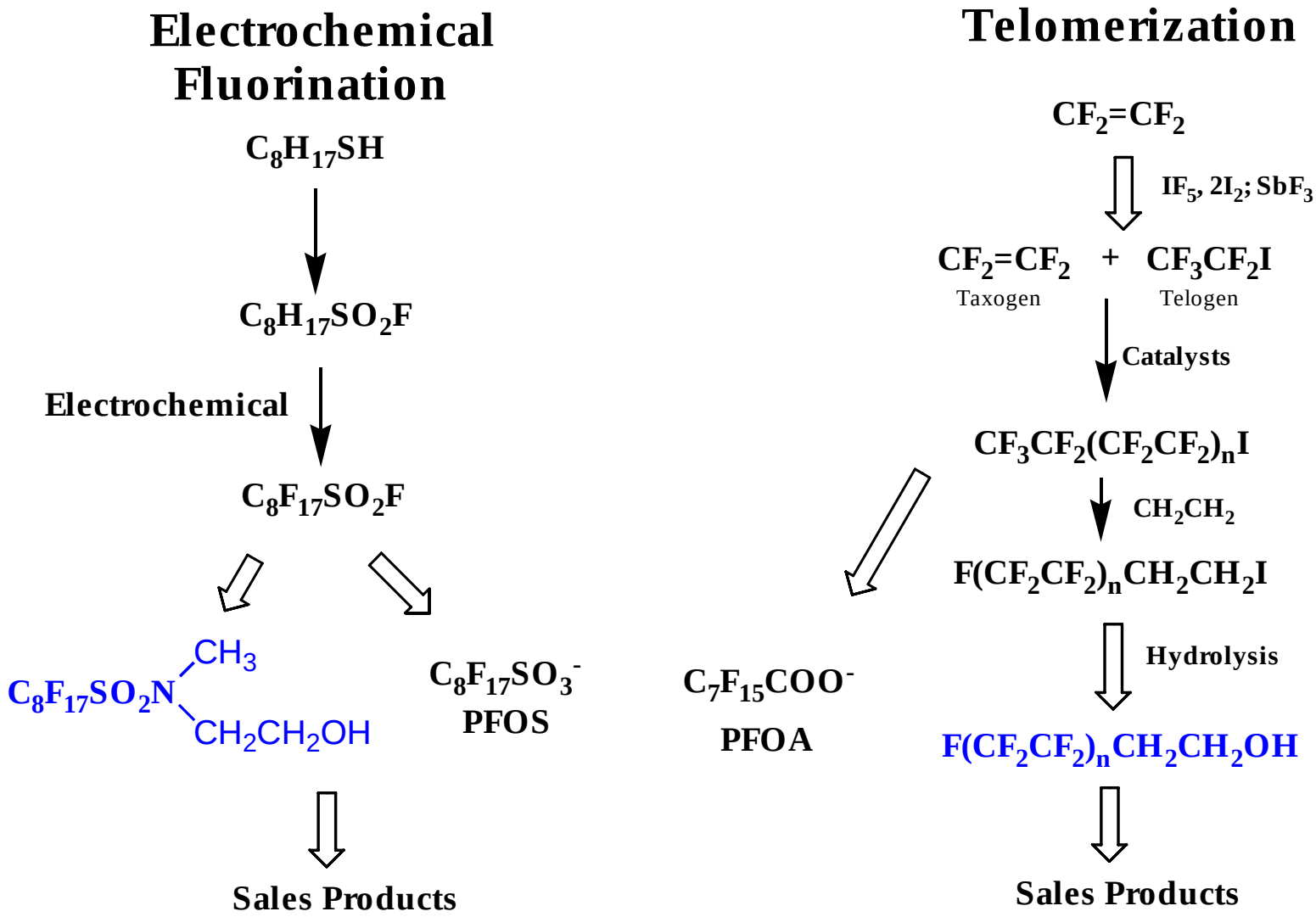


Ether



Urethane

Major Routes to Perfluoro Chains



[adapted from Kissa]

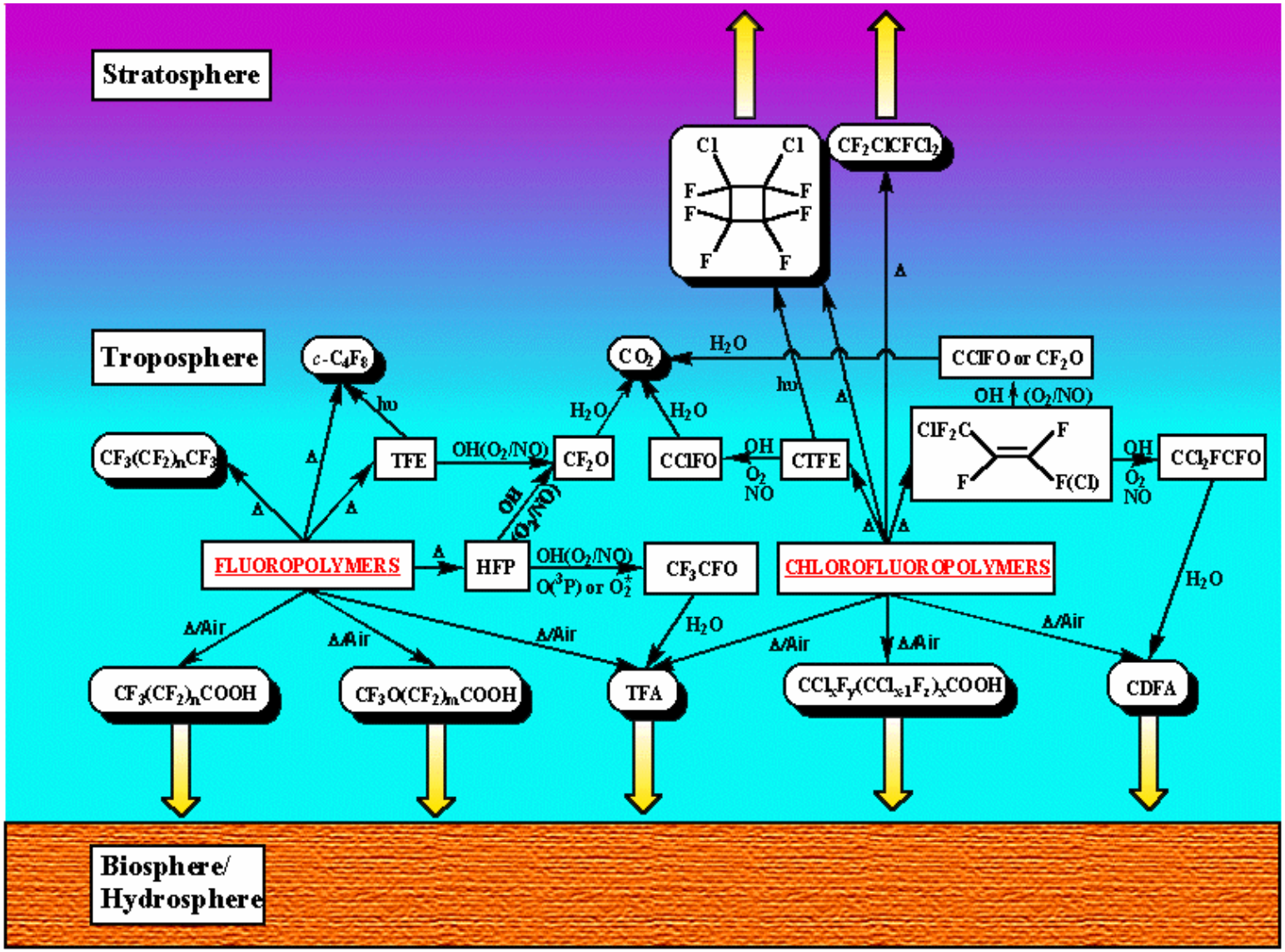
Direct releases of Perfluorinated Acids?

"Airport Foam Seeps into Creek"
Toronto Star, June 10, 2000

22,000 liters of AFFF; ~300 kg of PFOS!

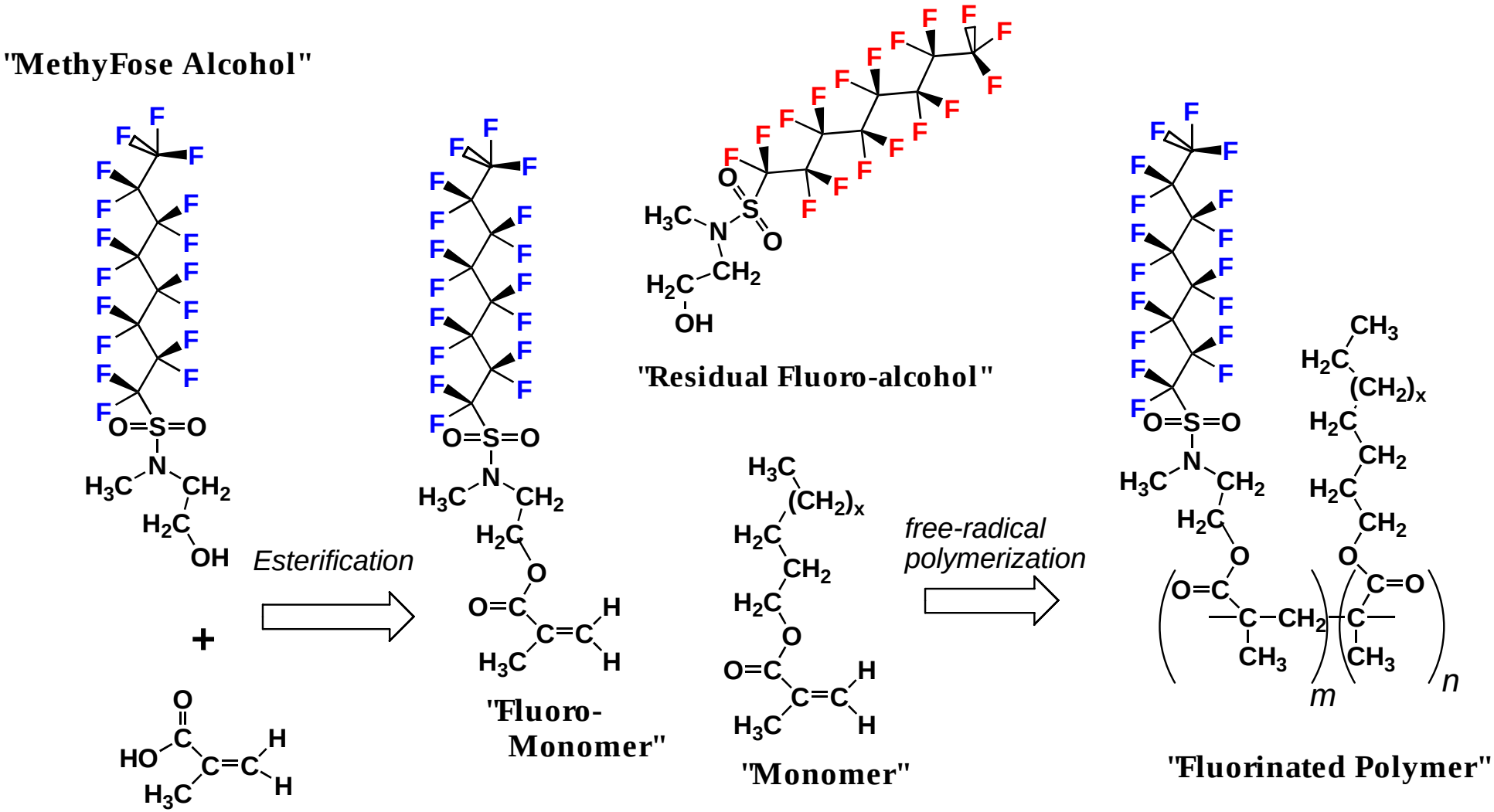
PTFE Leaching of PFOA

PTFE Thermolysis Products



Ellis, D.A., S.A. Mabury, J. Martin, and D.C.G. Muir. 2001. Thermolysis of fluoropolymers as a potential source of halogenated organic acids in the environment. *Nature*. **412**:321-324; Ellis, DA, JW Martin, DCG Muir, and SA Mabury. 2003. The Use of 19F NMR and Mass Spectrometry for the Elucidation of Novel Fluorinated Acid and Atmospheric Fluoroacid Precursors Evolved in the Thermolysis of Fluoropolymers. *Analyst*. **128**:756 – 764.

Nomenclature for Fluorinated Polymers



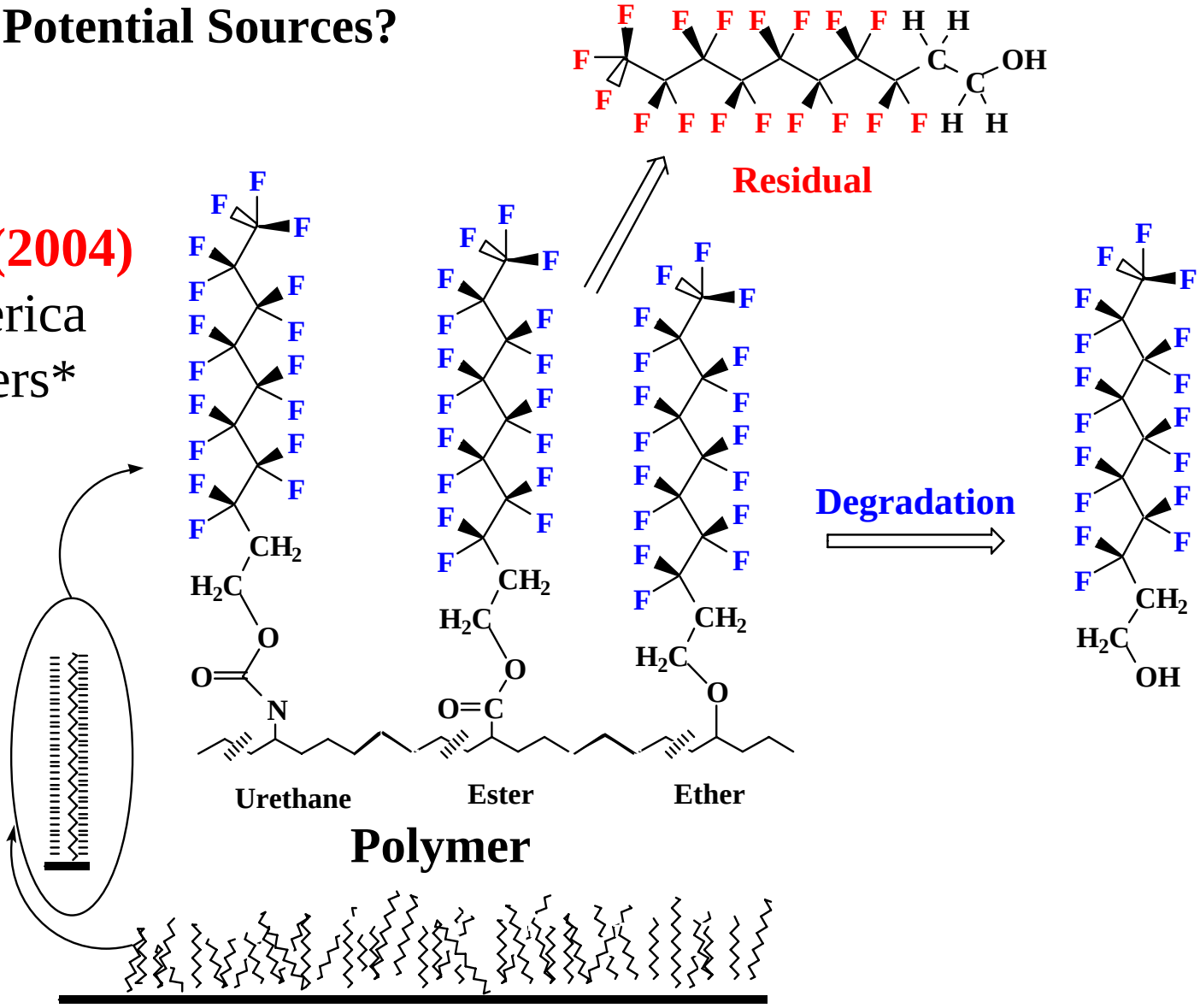
Fluoro alcohols ~ Fugitive Emissions from Residual Material OR Does the Linkage Chemistry Break?

Potential Sources?

11 to 14 x10^6 kg/yr (2004)

40% in North America

80% are in polymers*

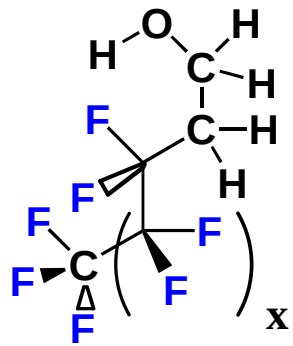


*Dupont Presentation to USEPA OPPT. Jan 31, 2005 US Public Docket AR226-1914

Posters: ENV004, 018, 023

Residuals could be important source of fluoroalcohols ...to the atmosphere

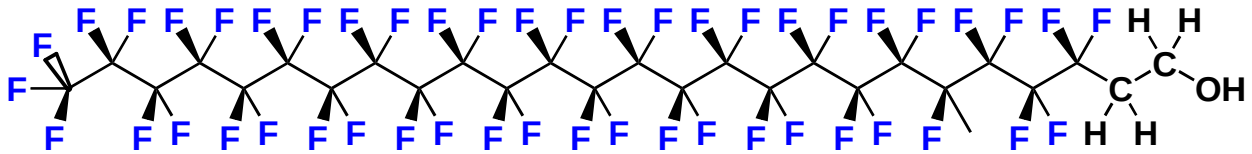
Fluorinated Material	Dry Weight % Residual
Polyfox-L-Diol	0.11 (0.03)
Teflon™ Advance	0.34 (0.20)
Zonyl™ FSO 100	1.03 (0.61)
Zonyl™ FSE	3.80 (1.09)
8:2 Methacrylate Monomer	0.04 (0.01)
Motomaster™ Windshield Washer Fluid w/ Teflon	0.36 (0.01)
Scotchgard™ Rug and Carpet Protector*	0.39 (0.06)



FTOH

n=3 or 6

Dinglasan, MJA and SA Mabury. 2005. *Environ. Sci. Technol.* In review

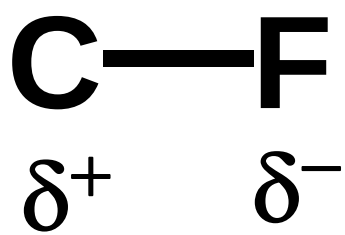


24:2 FTOH
"49 Fluorines"

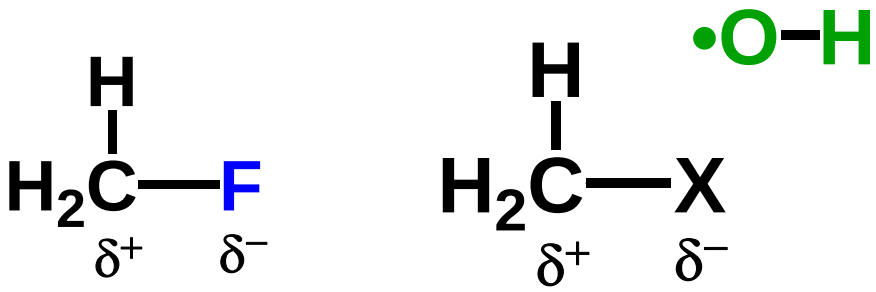
Tentatively identified in a telomer phosphate mixture via GC/MS; see Poster ANA044

Anything Interesting about the C-F bond?

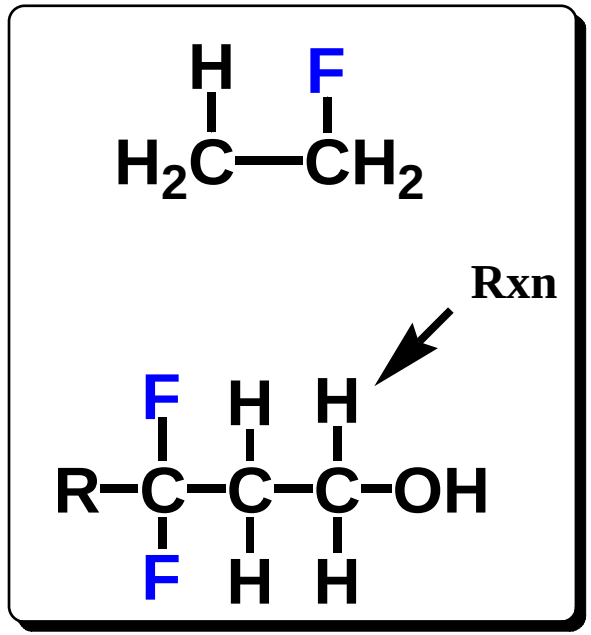
	bond length C-X (A)	Bond Strength C-X (kcal/mol)	EN	Van der Waal's radius (A)	Hydradation X^- (kcal/mol)
H	1.09	99	2.2	1.20	-
F	1.39	110	4.0	1.35	117
Cl	1.78	85	3.0	1.80	84
Br	1.93	71	2.8	1.95	78



What does the Fluorine atom do to reactivity towards Oxidation?



X	f(x)
F	0.094
Cl	0.38
Br	0.28
CF_3	0.071
OH	3.4

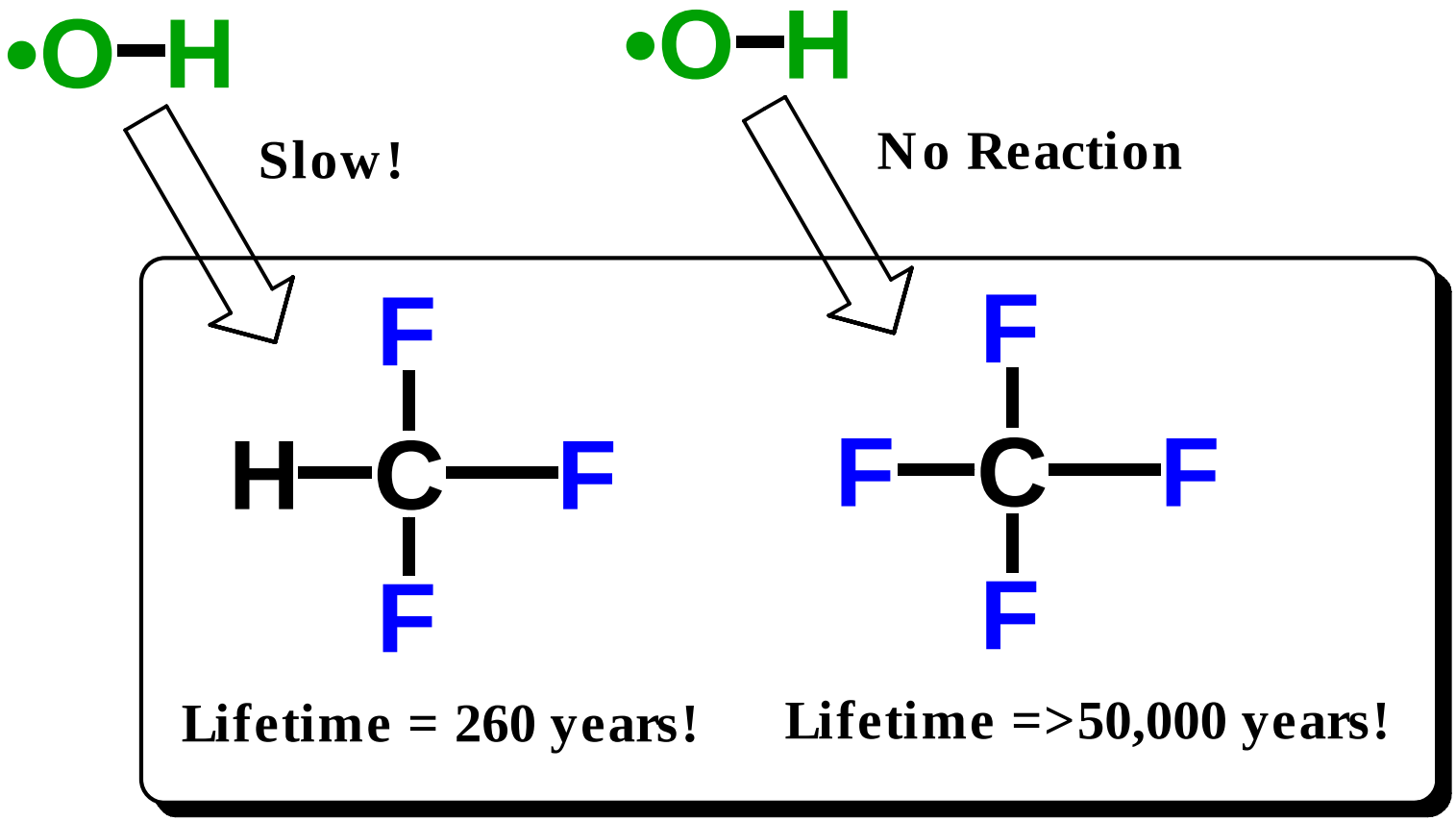


Note: Similar story for ring oxidations.

Slows it way down!

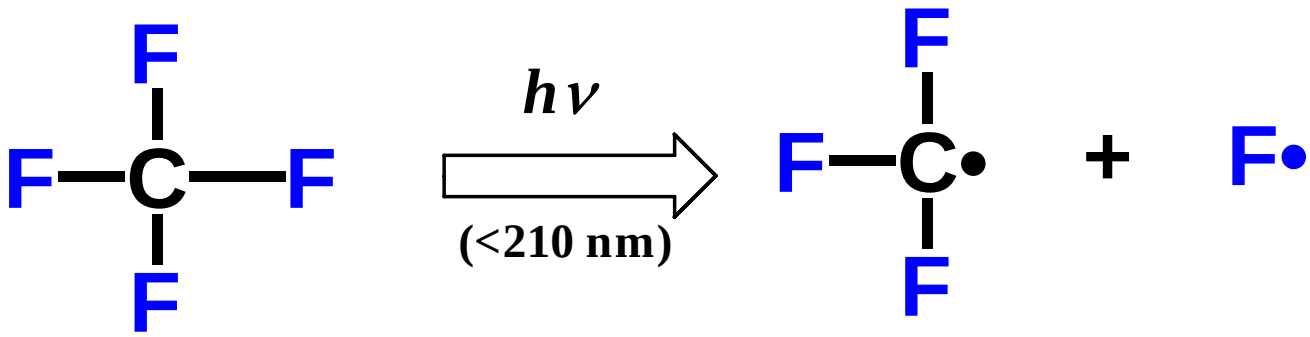
Kwok & Atkinson; 1995; Atmo Env. 29:1685-1695.

HFCs are slow…PFCs are like diamonds!



Only option is photolysis ...but where?

way up high!



Lifetime =>50,000 years!

Ultimate Fate? Photolysis in upper atmosphere (highly energetic photons)

Does F• cause O_3 destruction like Cl or Br? NO! [10^4 less than Cl]

Why?

$$F + O_2 \underset{\leftarrow}{\overset{M}{\rightarrow}} FO_2 \quad \text{(eq far to the right)}$$

$$FO_2 + O_3 \rightarrow FO + 2O_2 \quad \text{(very slow)}$$

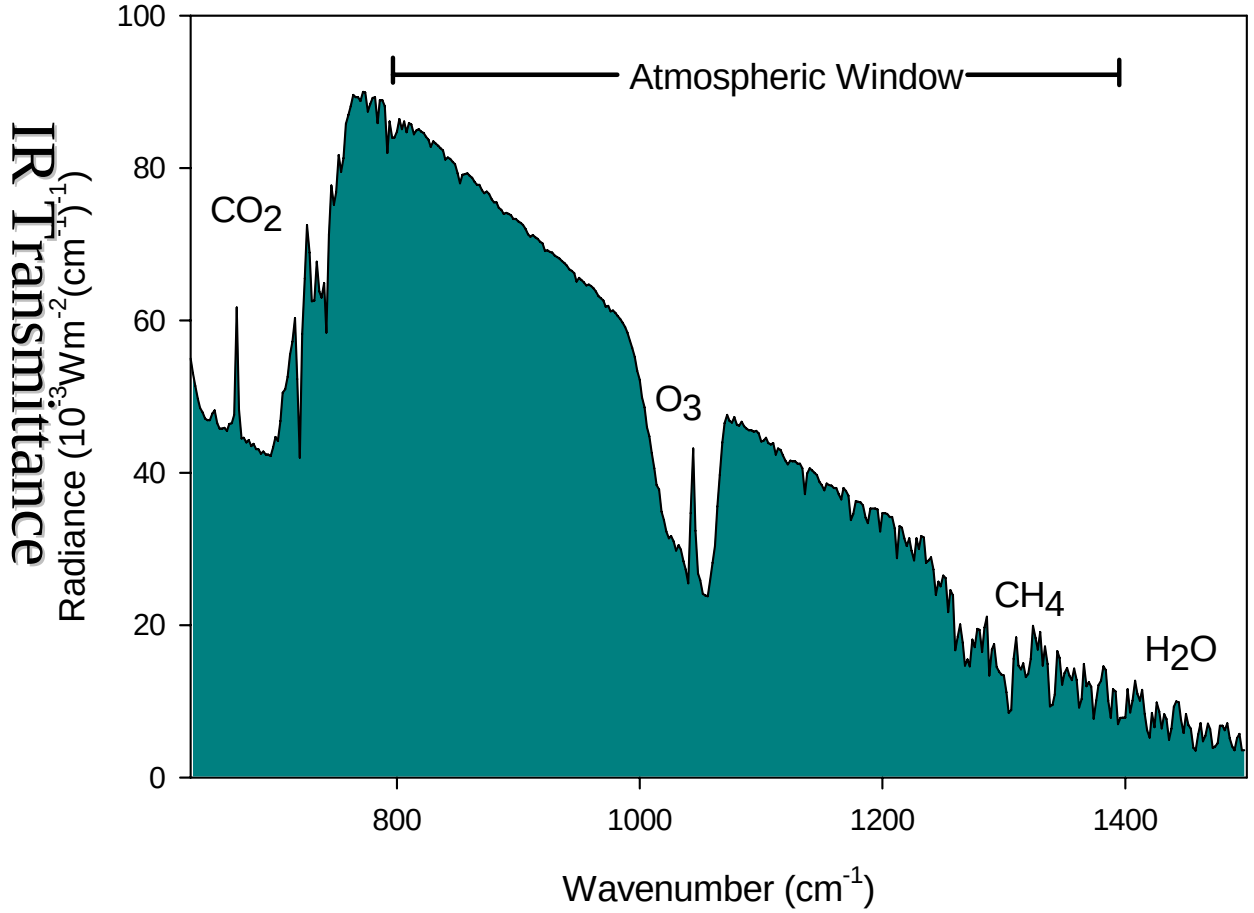
$$F + CH_4 \rightarrow HF + CH_3 \quad \text{(very fast)}$$

$$F + H_2O \rightarrow HF + OH \quad \text{(very fast; exothermic!)}$$

Any problems percolating way up there?

$F_3C{-}CF_3$

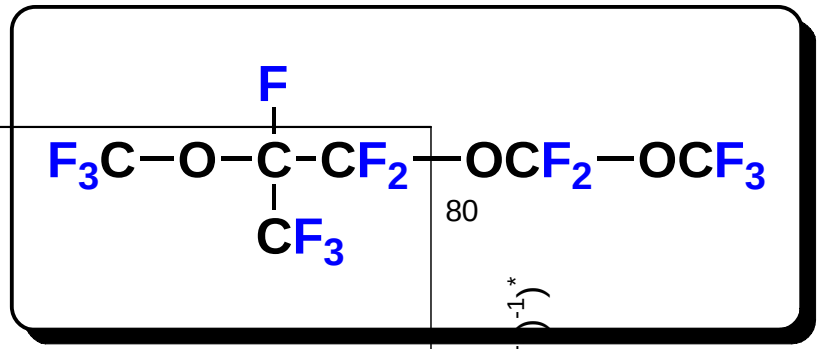
Lifetime = 10,000 yrs
Radiative Efficiency = 0.26 W m^{-2} ppb^{-1}
GWP (100 yr) = 11,900 (where CO2 = 1)
Year 2000 concentration: 3 pptv

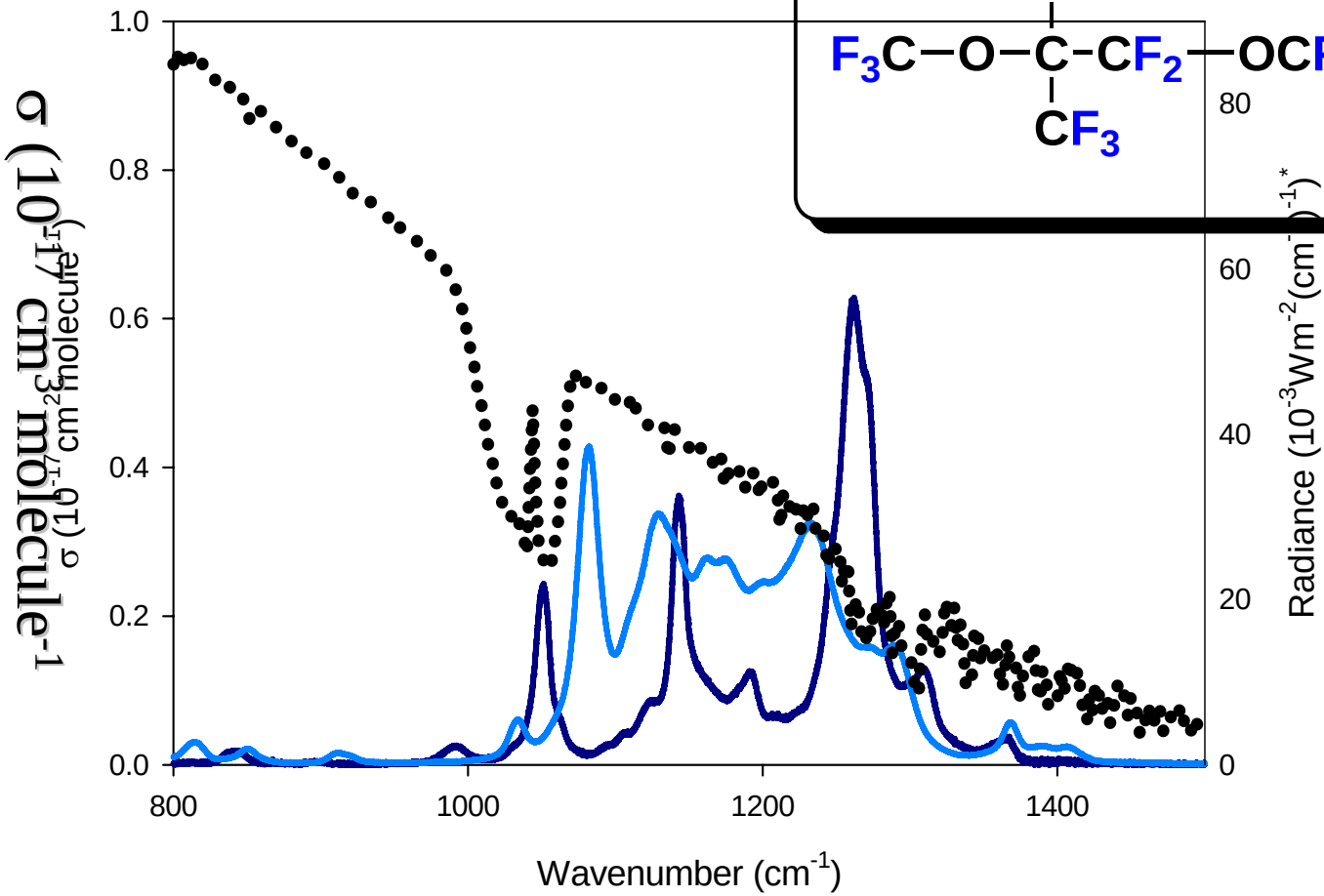


F_5S-CF_3

Lifetime = >1,000 yrs
Radiative Efficiency = 0.59 W m^{-2} ppb^{-1}
GWP (100 yr) = >17,500 (where CO2 = 1)
Year 2000 concentration: 4 pptv

(Sturges et al, 2000, Science 289:611-613)





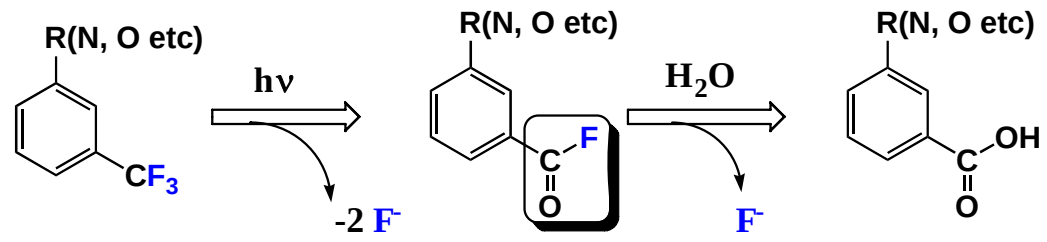
* Calculated for mid-altitude during winter using calculator found on http://geosci.uchicago.edu/~archer/cgimodels/radiation.html

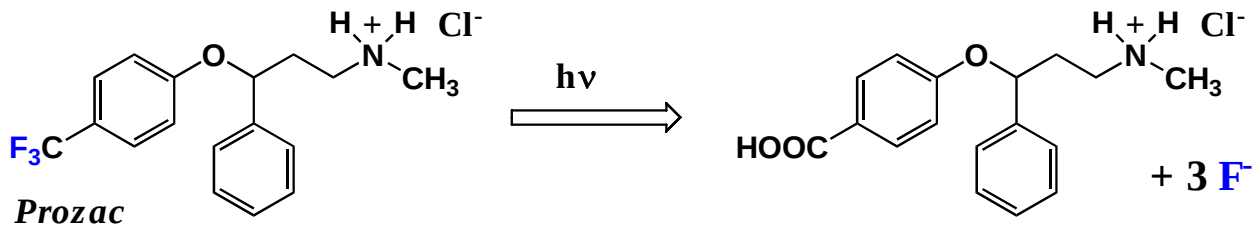
Posters: ENV025 & ANA030

Can you break a C-F bond?

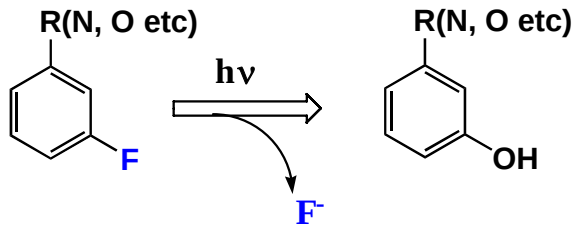
Only in special cases or conditions

Photolysis in Natural Waters



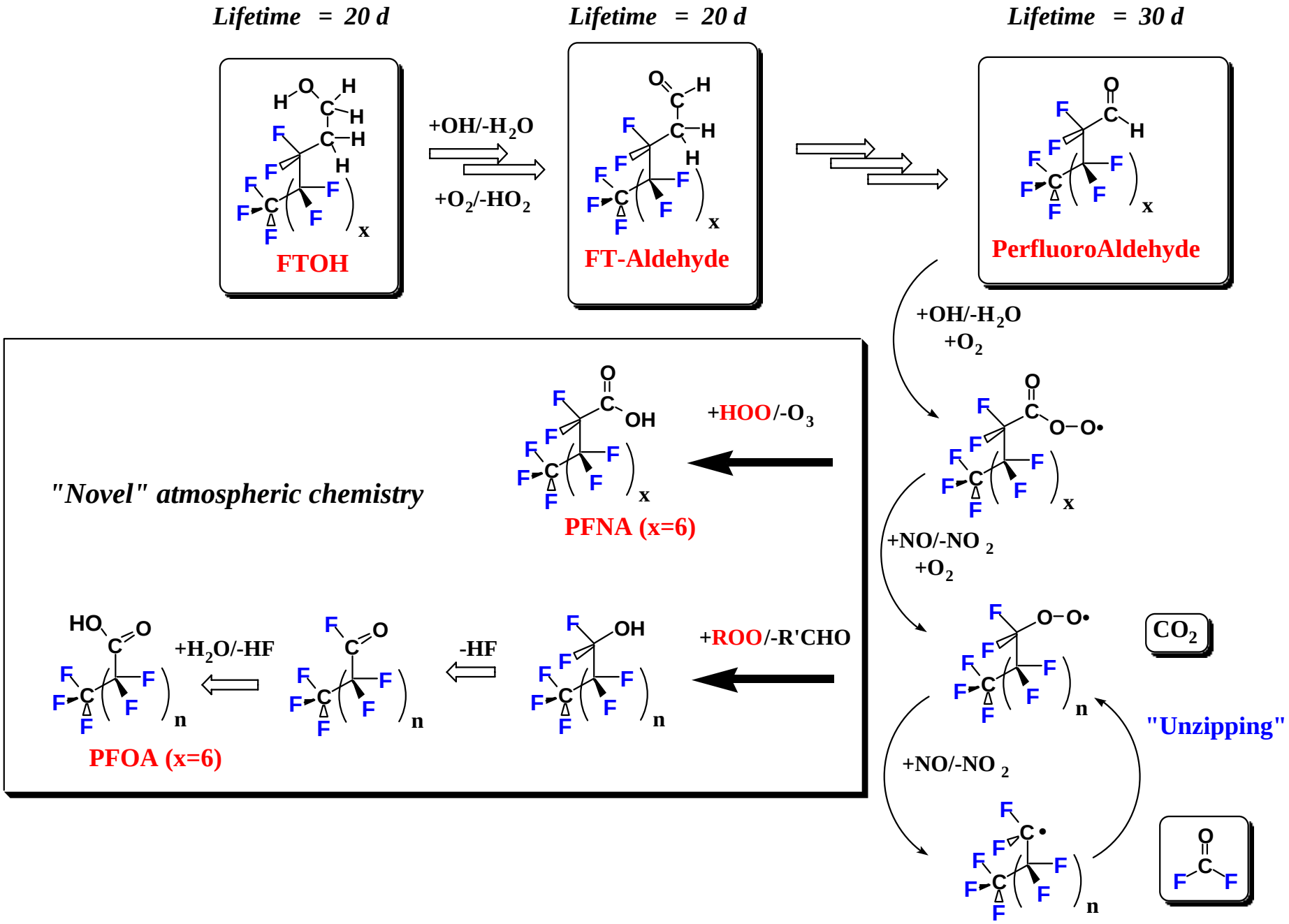


Prozac

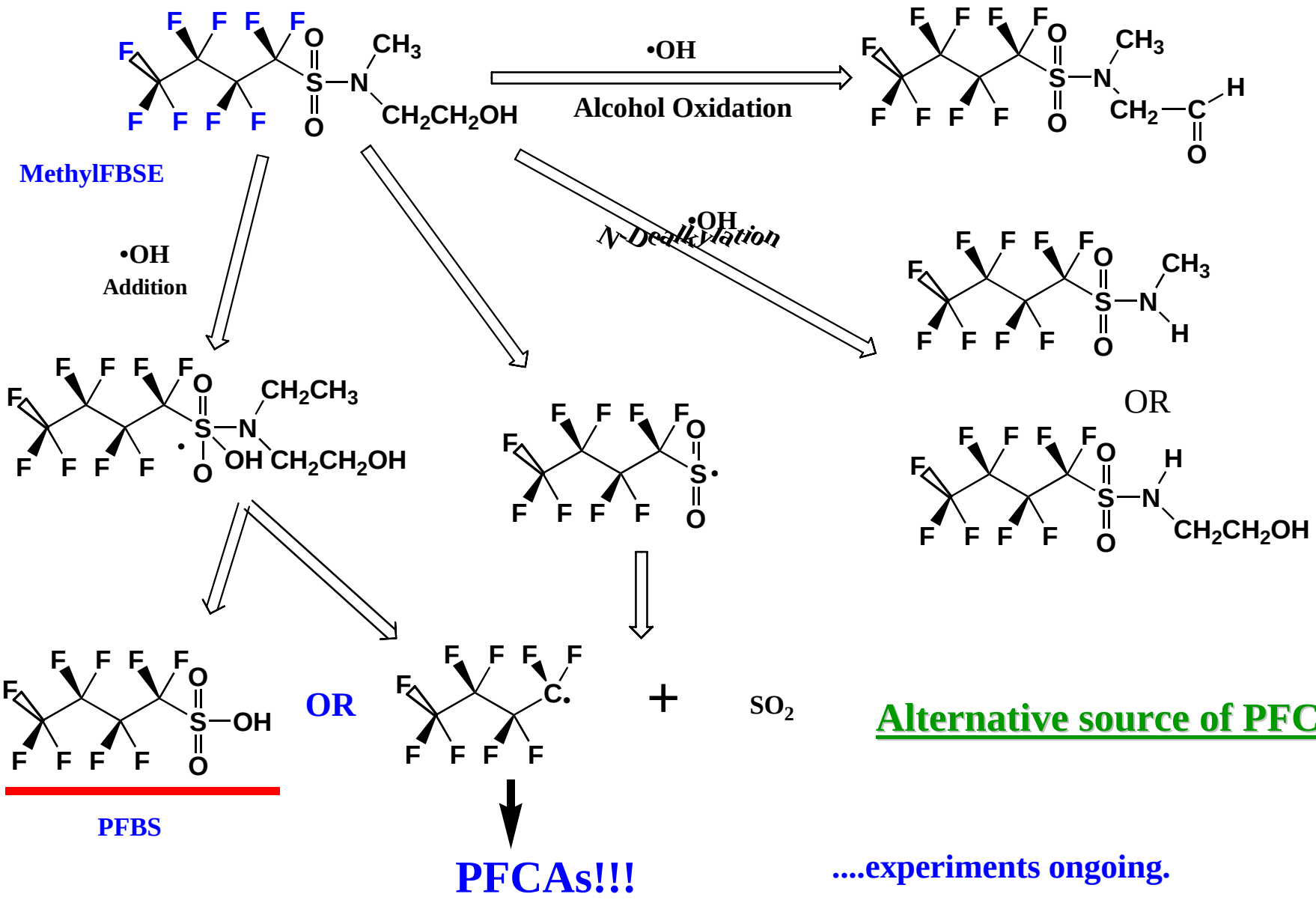


Br>Cl>F

Overall Atmospheric Chemistry of FTOHs



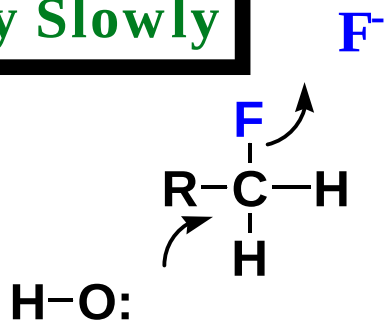
Do the Sulfamidoethanols Degrade to Acids in the Atmosphere?



Posters: ENV017 & 021

Hydrolysis?

Only Slowly



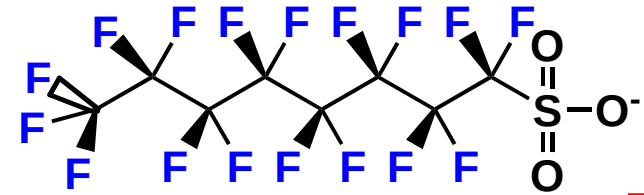
Why?

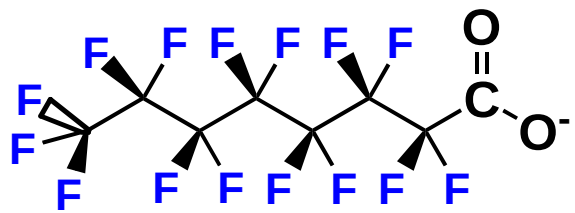
- F^- is a VERY poor leaving group;
- Thus SN1 and SN2 only go slowly;
- polyfluorination increases 'steric' issues;

	half-life (pH 7)
CH_3F	~30 yrs
CH_3Br	1 yr
$(CH_3)_3CF$	50 days
$(CH_3)_3CCl$	23 sec

	pK_a
HCl	Low
H_3PO_4	2.12
HF	3.14
Benzoic acid	4.20
TFA	0.5
PFOS	Extremely Low
PFOA	~2

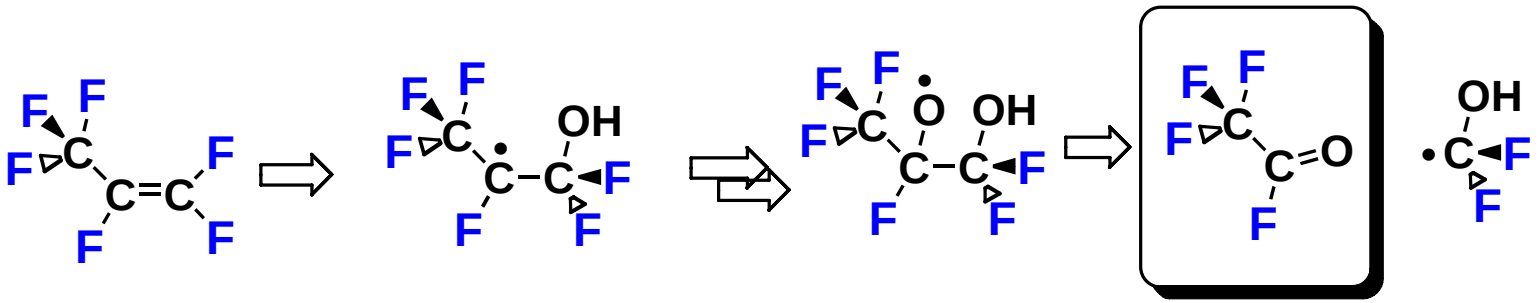
In the environment?

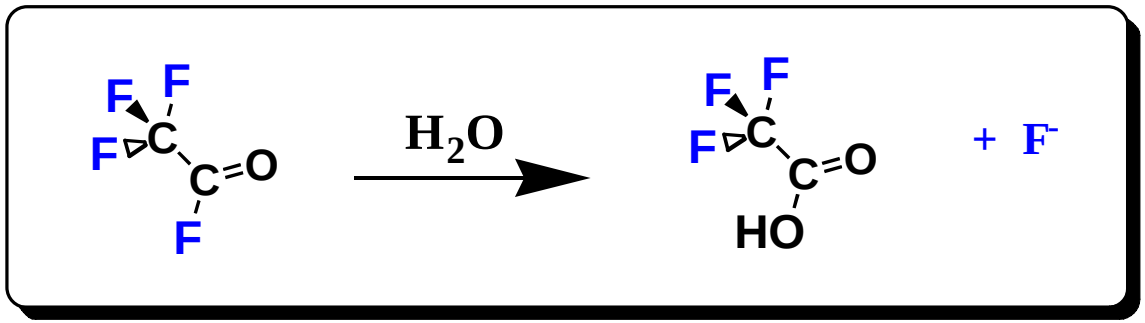


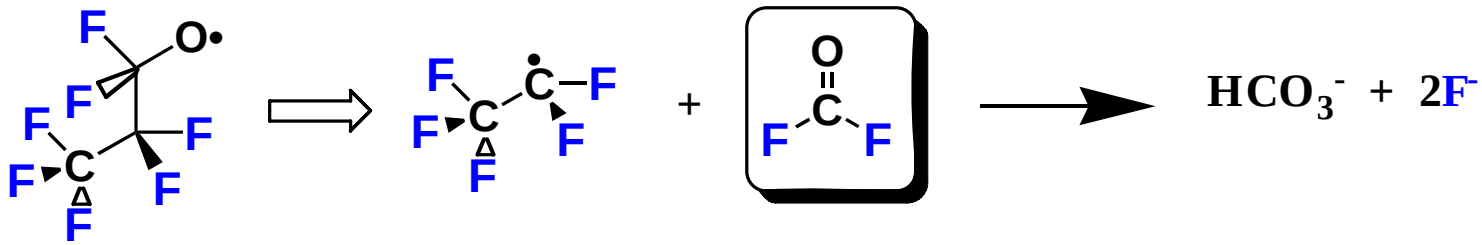


Likely as salts

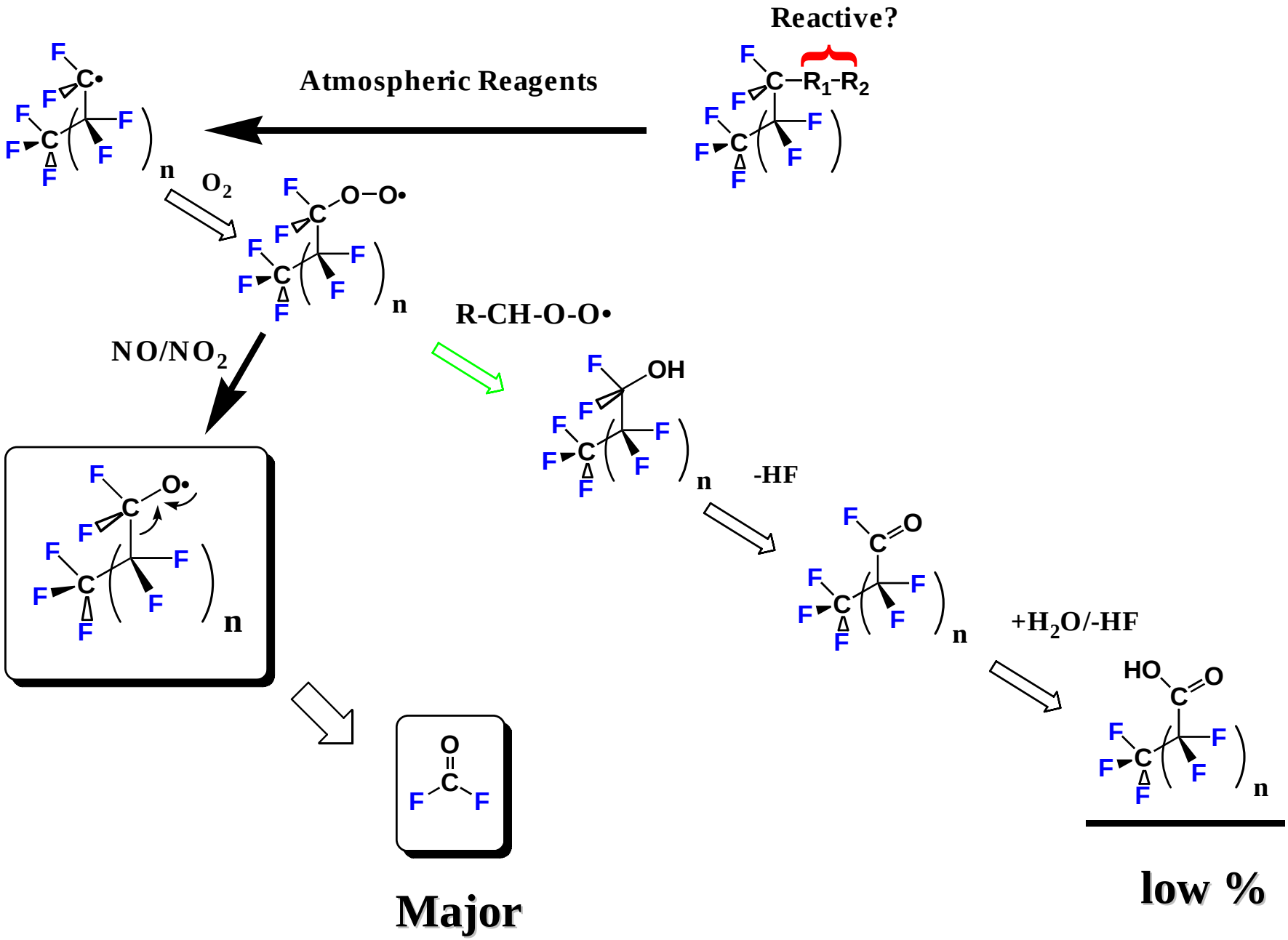
Except in special cases...where F^- is pushed!





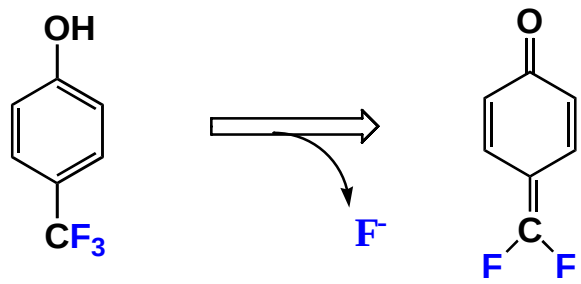


Fate of Perfluorocarbon Radicals



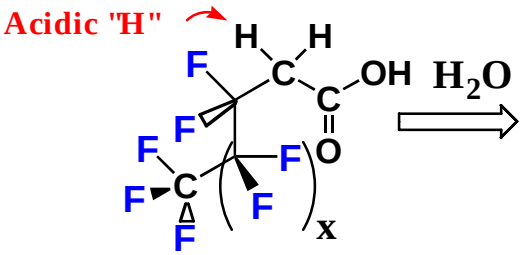
If the right 'architecture' then ELIMINATE?

Elimination

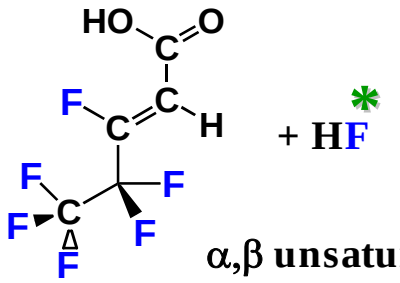


Stable

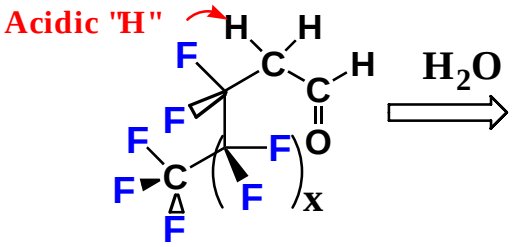
β-Elimination



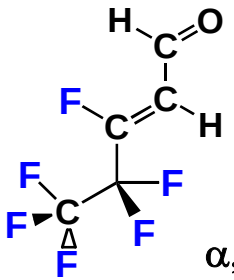
Telomer Acids



α,β unsaturated acids



Telomer Aldehyde



α,β unsaturated aldehydes

abiotic; x=6, pH 7, T=23C
~35 days

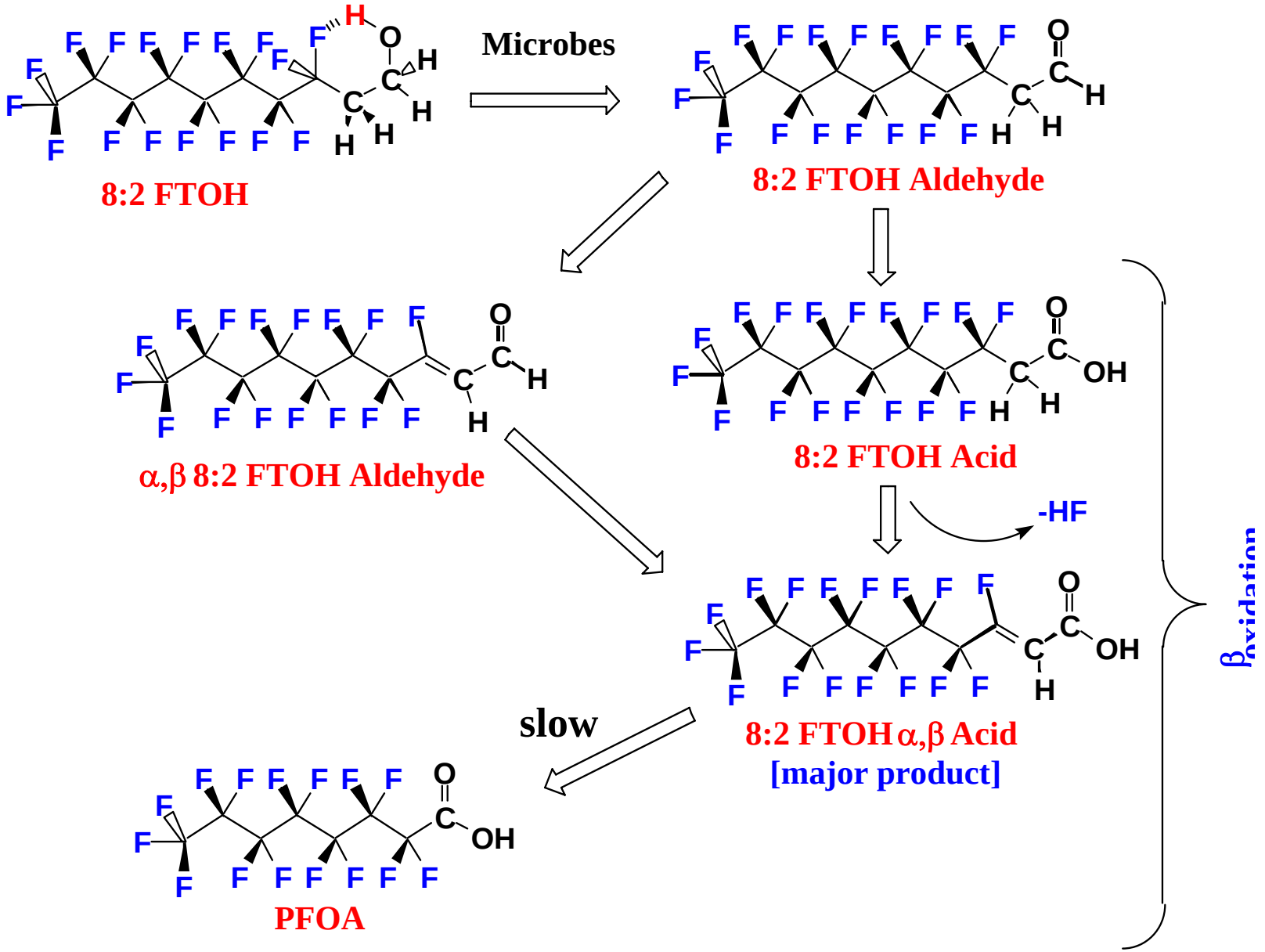
biotic (bacteria); x=6, pH 7, T=23C
~14 days

biotic (rats); x=6, pH 7.2, T=23C
~very fast

Biotic & Abiotic are much Faster

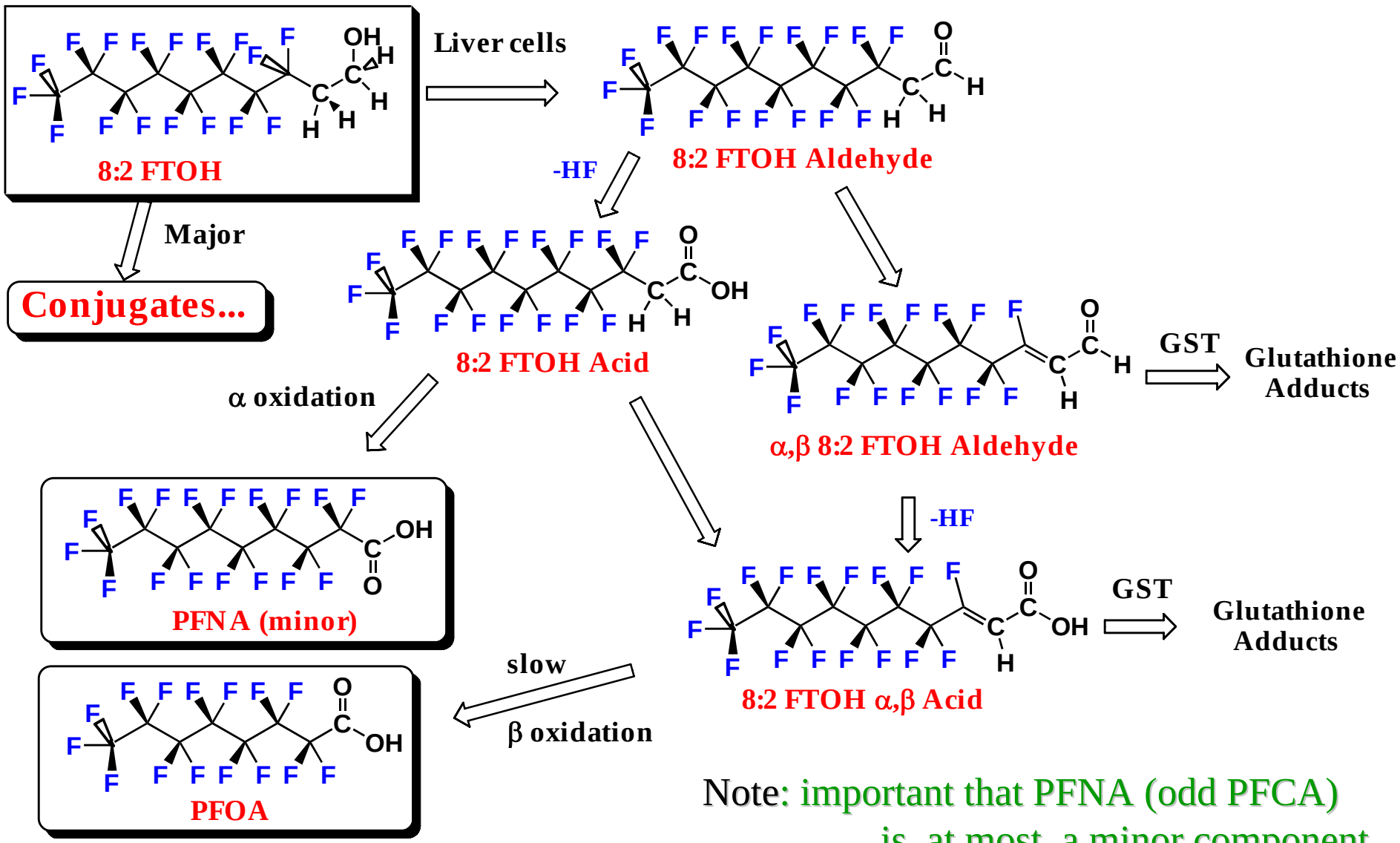
*SEE Poster TOX008; is HF the cause of the high toxicity of 10:2 FTCA?

Microbial Metabolism Pathway ~



Posters: ENV011 & 022

Rat Liver Metabolism Pathway ~



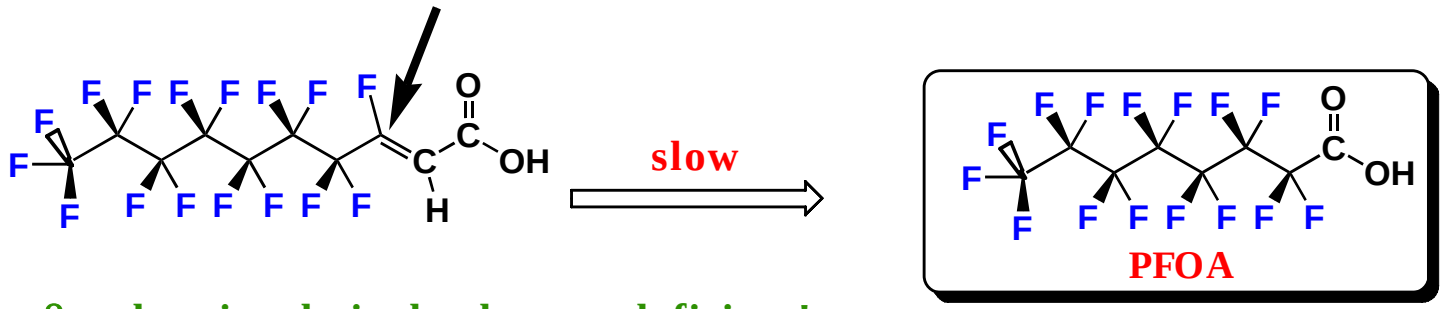
Note: important that PFNA (odd PFCA) is, at most, a minor component.

Posters: TOX010

Hagen, Belisle, et al, 1981. Anal Biochem. 118:336-343; Martin, JW, SA Mabury, and PJ O'Brien. 2005. Metabolic Products and Pathways of Fluorotelomer Alcohols in Isolated Rat Hepatocytes. *Chemico-Biological Inter* **In press**.

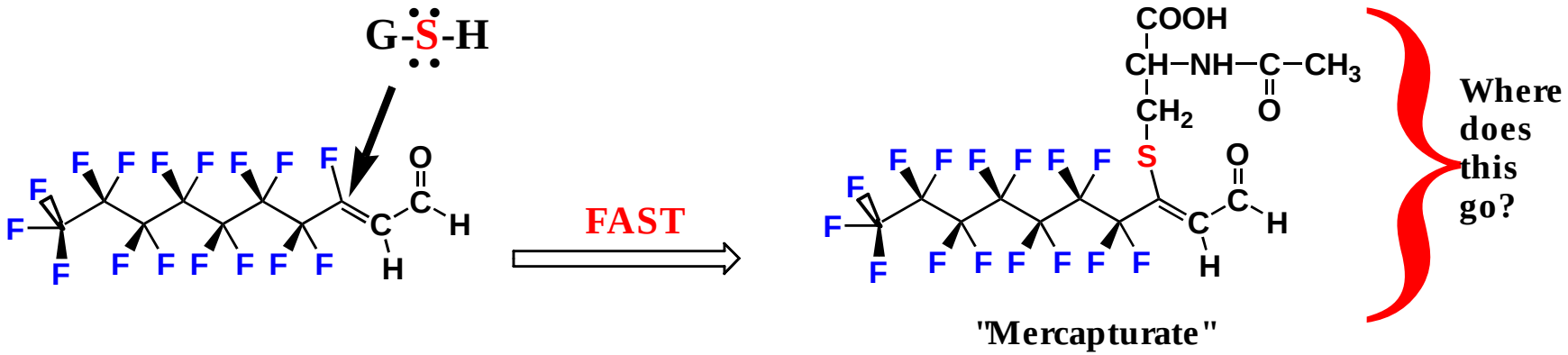
Why is this reaction so slow?

• OH or FeO+ are strong electrophiles but...



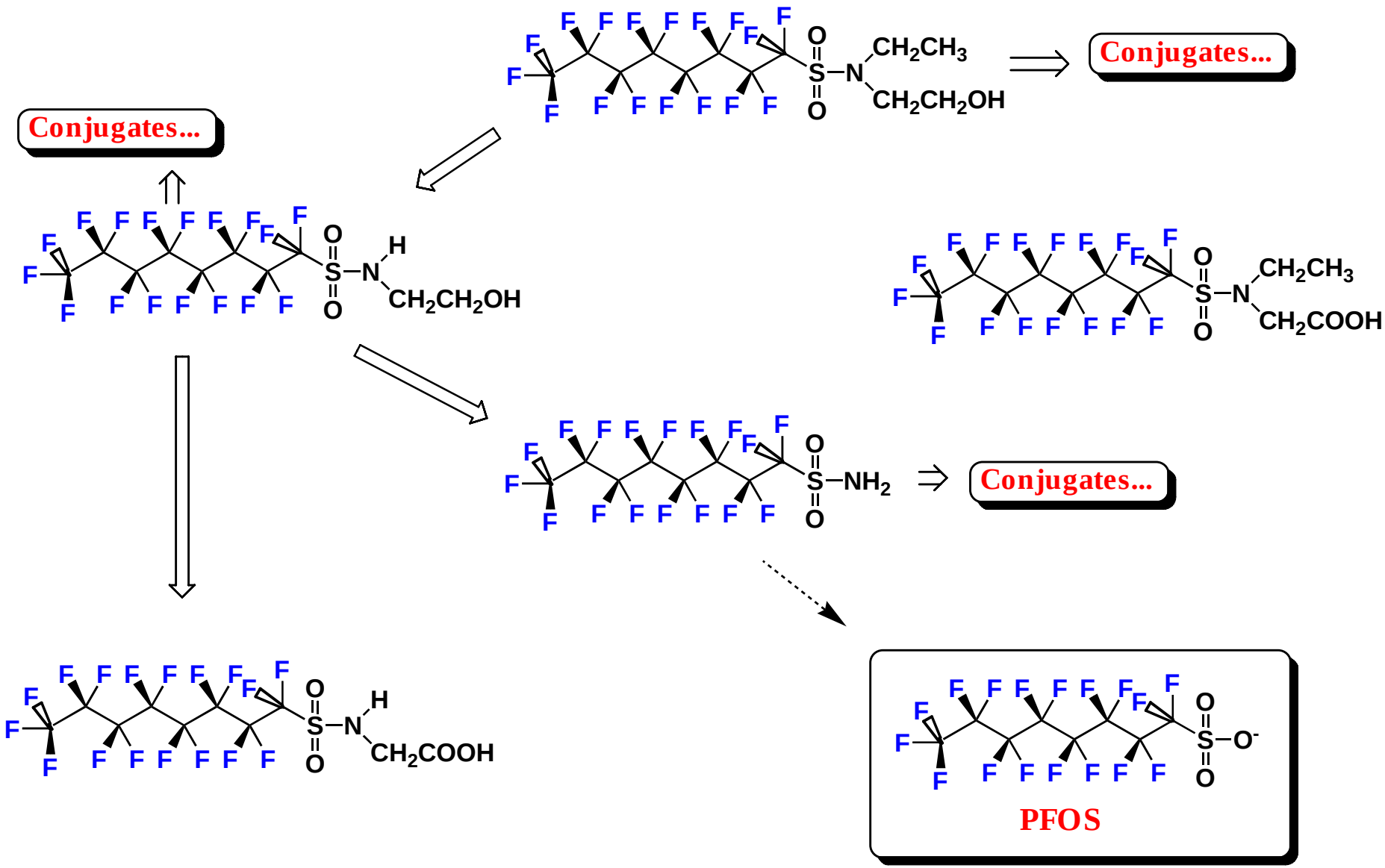
...the β carbon is relatively electron deficient!

Thus is it surprising the β carbon is reactive towards nucleophiles?



NO! One hopes it is GSH and not one of the nucelophilic centres on a protein or in DNA.

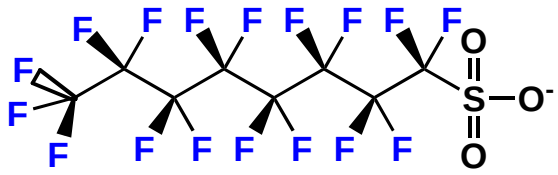
Human & Rat Biotransformation of EthylFose

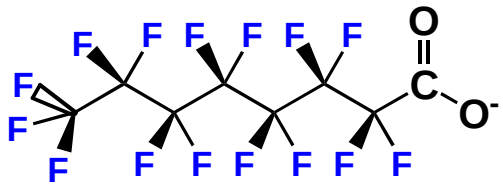


Xu et al, 2004. Chem. Res. Toxicol. 17: 767-775; Tomy et al. 2004. ES&T (Fish Livers)

Posters: ENV006, 014, 015,

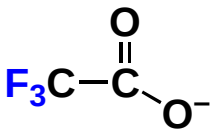
Okay but what about those perfluorinated acids that are all the rage?





No Reactions @Environmentally Relevant Conditions....even examples under 'extreme conditions' are rare or hard to decipher.

One persuasive example:



Engineered "bioreactor"

over 90 days

Measured evolution of F^-

Kim et al, 2000. Env Eng Sci. 17:

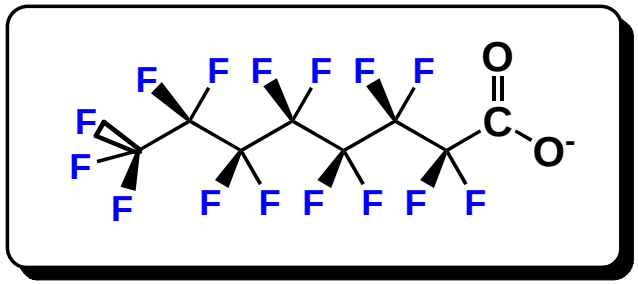
Yes…pretty boring indeed with respect to Reactions!

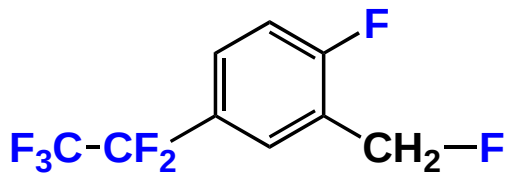
Water Solubility and Partitioning

Kow Fragments

X	f	f^{θ}
X-F	-0.38	0.37
X-Cl	0.06	0.94
X-Br	0.20	1.09
X-I	0.59	1.35
X-COOH	-1.11	-0.03
$X\text{-}COO^-$	-5.19	-4.13
X-OH	-1.64	-0.44

Hansch & Leo; EOC 1st Edition



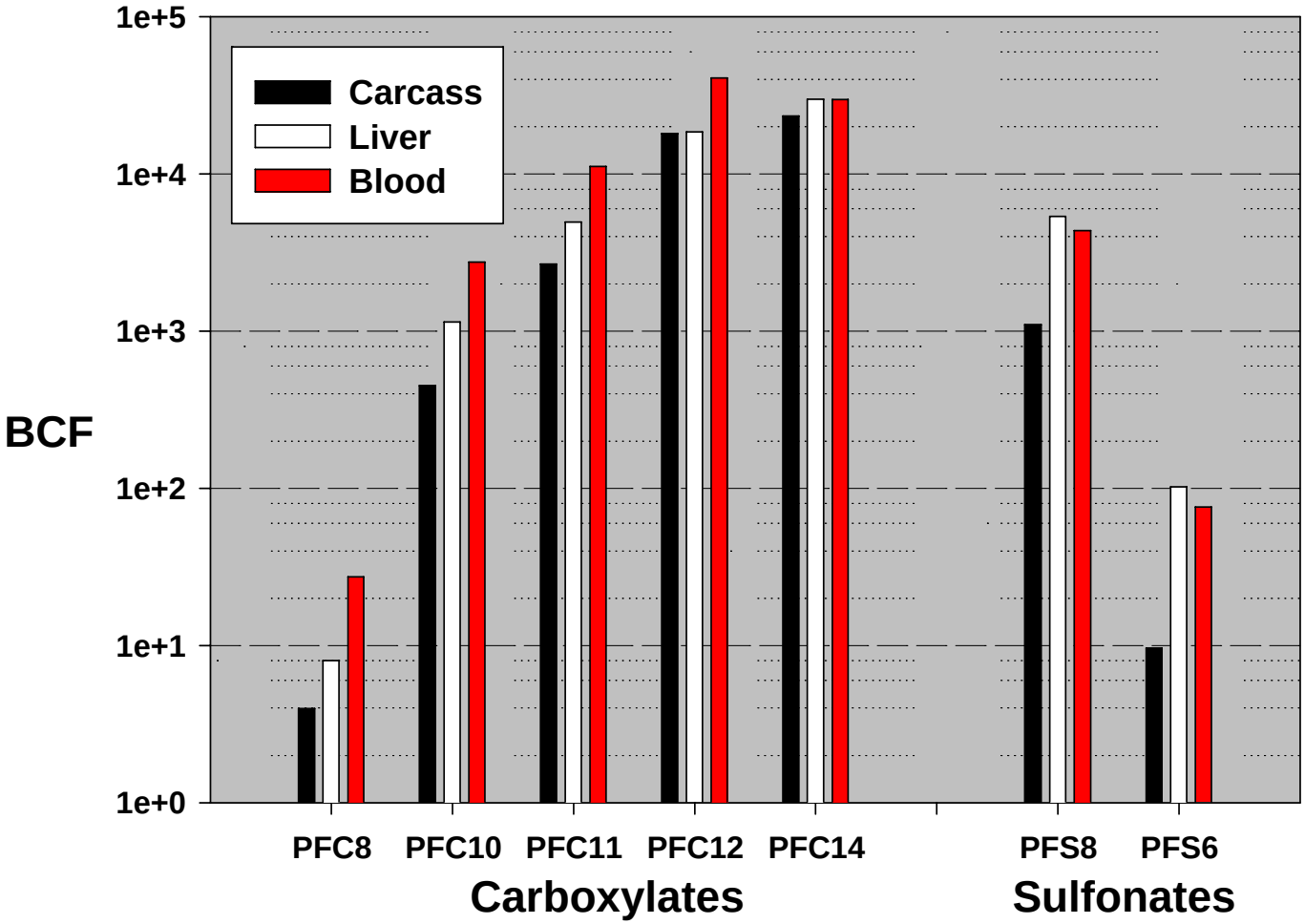


Kow Correction Factors "electronic effects"

Nearby Polyhalogenation	
2 on same C	0.60
3 on same C	1.59
2 on adjacent single-bonded C	0.28
3 on adjacent single-bonded C	0.56
and so forth...	

$$\text{Water Solubility} \propto \frac{1}{\text{Kow}}$$

BCF/BAF of PFCAs



$$BCF = k_u / k_d$$

Additional CF_2 results in a ~**7x** increase in the BCF.

Martin, J., S.A. Mabury, K.S. Solomon, D.C.G. Muir. 2003 Bioconcentration and Tissue Distribution of Perfluorinated Acids in Rainbow Trout (*Oncorhynchus mykiss* Environ. Tox. Chem. **22**: 189-195.

Martin, J., S.A. Mabury, K.S. Solomon, D.C.G. Muir. 2003 Dietary Accumulation of Perfluorinated Acids in Rainbow Trout (*Oncorhynchus mykiss*. Environ. Tox. Chem. **22:**196-204.

Fluoros Flying?

V.P. Fragments

X	f	f^{θ}
X-F	0.07	0.21
X-Cl	-0.79	-0.53
X-Br	-1.18	-0.84
$X-CF_3$	-0.20	0.32
$X-CCl_3$	-1.89	-2.63
$X-CBr_3$	-3.47	na
X-COOH	-3.67	-4.69

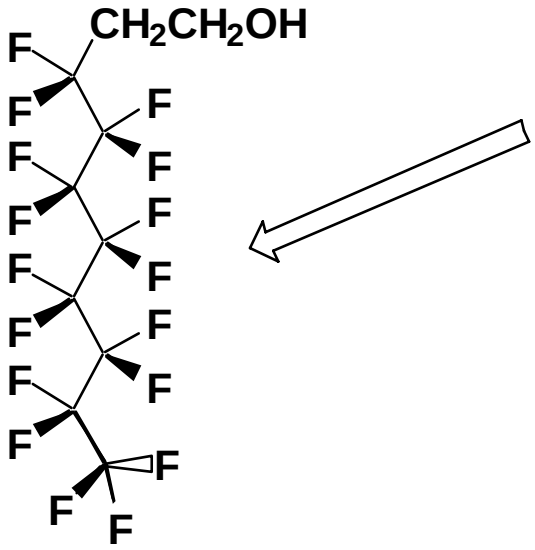
Simmons; 1999. JAFC; 47:1711-1716

Henry's Law Fragments

X	f	f^{θ}
C-F	+0.50	
C-Cl	-0.30	+0.14
C-Br	-0.87	-0.21
C-OH	-3.21	
$C-NO_2$	-3.10	-1.83

Hine & Mookerjee 1975 in EOC 1st Edition

8:2 FTOH by V.P. and M.W.



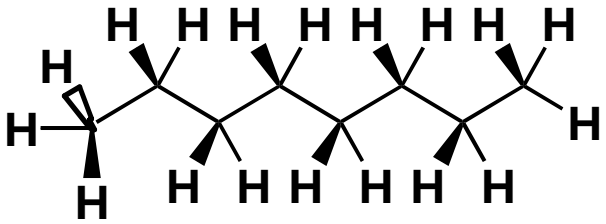
	M.W.	V.P. (Pa)
8:2 FTOH	464	212*
Cl_8-Dioxin	460	0.0000000001
PCB 153	360	0.0001
Di-(2-ethylhexyl) pthalate	390	0.0019
n-Decane	142	173
CBr_3H	252	724
1,2 Dichlorobenzene	147	200
Ethoxybenzene	122	204

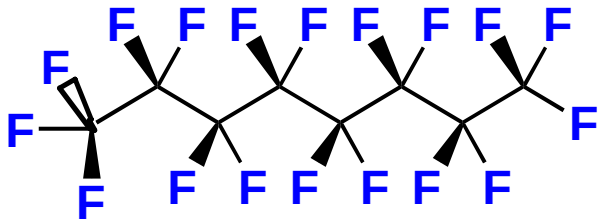
Data from "EOC" Schwarzenbach *et al* ;
*Data from Lei, Mabury, et al, unpublished data.

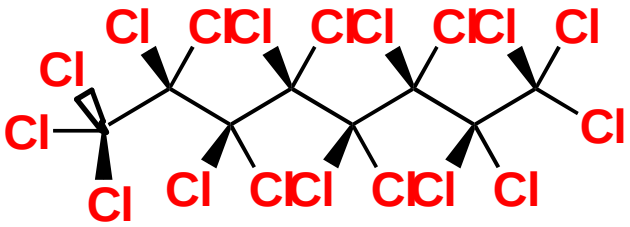
So are Fluorocarbons very Polarizable? NO!

α = polarizability
R.I. = Refractive Index
M = Molar Volume

Per...Octanes







"make believe molecule"

M.W.	R.I.[1]	Density[1]	M[2] (cm^3/mole)	V.P. (Pa)	α^5 $\AA^3$
114	1.398	0.703	124	1819[4]	15.8
438	1.282	1.766	155	4677[3]	15.2
890	?????	?????	?	10^{-3} *	47.1

[1]Aldrich; [2]McGowan *et al*; [3]CRC Online; [4]Schwarzenbach
[5]Calculated with Gaussian by M. Staikova; *for $C_{10}Cl_6H_{16}$

FluoroAlcohol Physical Properties

	P (Pa)	Log K_{aw}	Log K_{oa}	C^{w}_{sat}	Log $K_{ow}^{?}$
4:2 FTOH	1670; 992; 489(a)	1.8	3.3		2.0
6:2 FTOH	876; 713; 107(a)	1.7	3.6		3.3
8:2 FTOH	227; 254; 2;4(b)	1.3	4.2	148	4.9
10:2 FTOH	53; 144; 0.7(a)		4.8		2.7
NEtFosa	7; 0.24		5.9		4.1
NMeFose	0.7;0.0004		6.8		
NEtFose	0.35; 0.0017; 0.79		7.1		

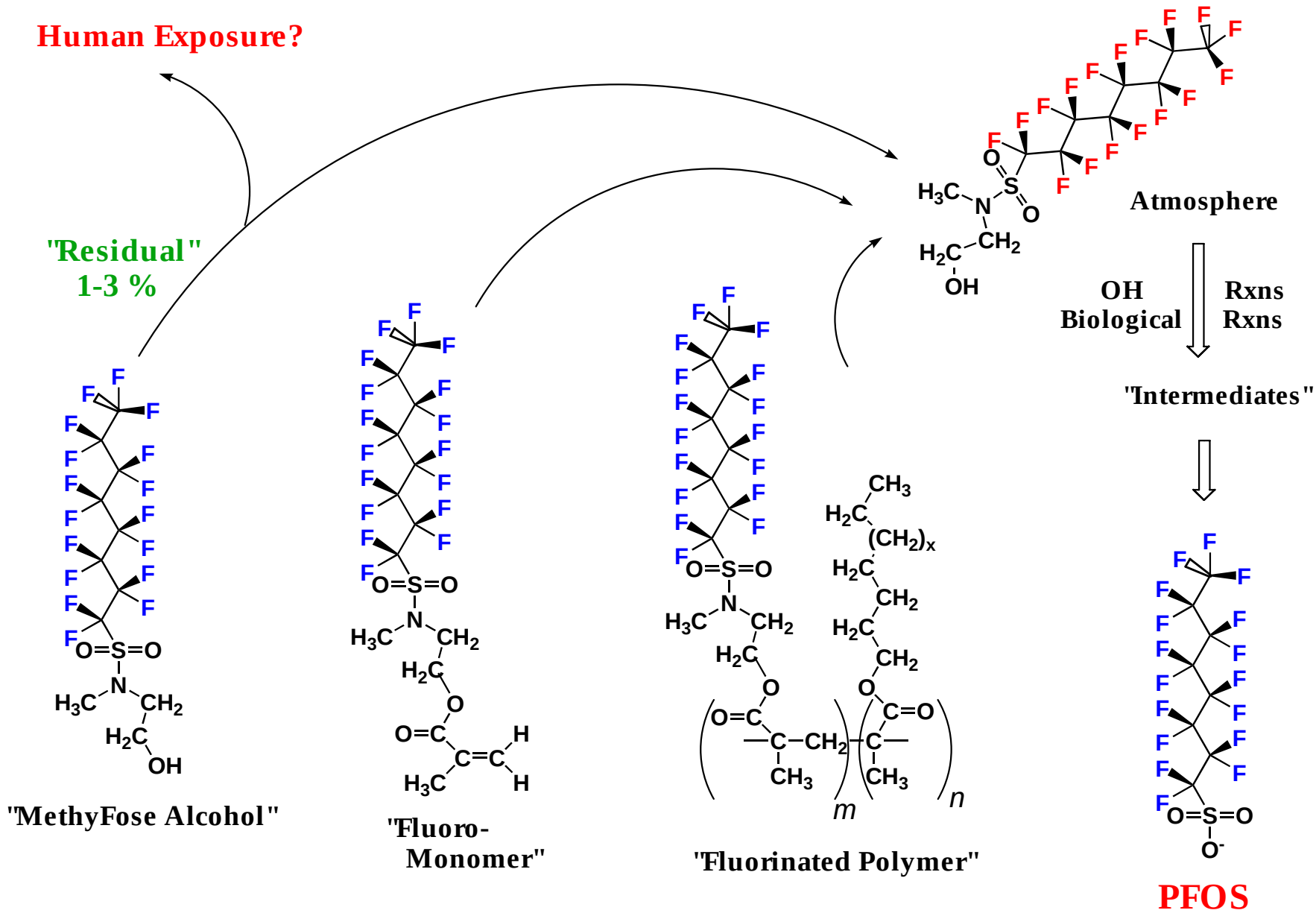
R^2=0.99

Stock et al 2004. ES&T. 38:1693-1699; Lei et al, 2004. J Chem Eng Data 49:1013-1022; 25C
Krusic et al, J Phys Chem A; 2005; 109:6232-6241; (a) calculated at 35C; (b) calculated at 21C;
Schoeib et al,
3M Values OPPT Docs
Bonin, Lau, Ellis, & Mabury, unpublished data.

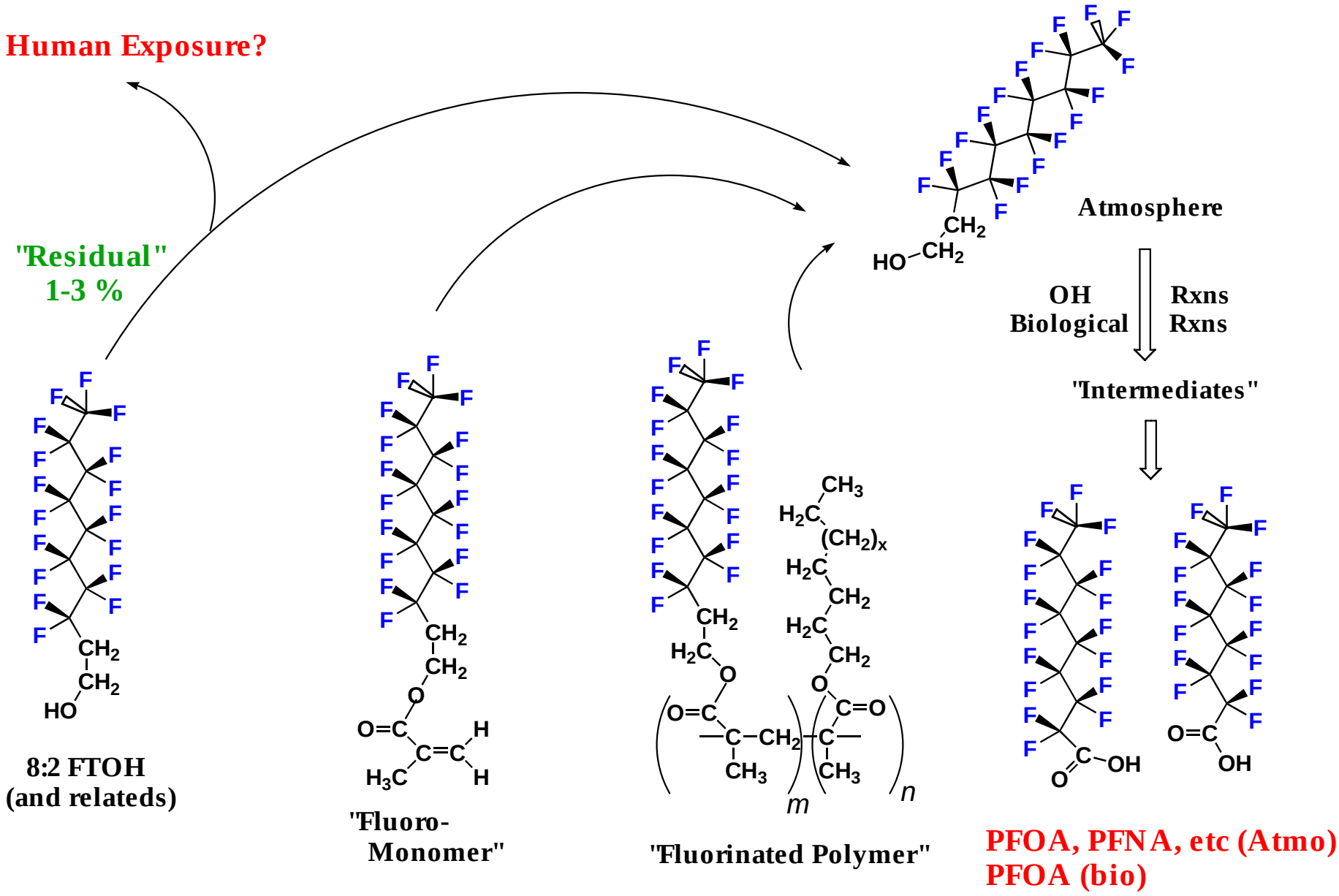
Summary…major points:

- **Organofluorines are intriguing ~ lots to learn and interesting science to do;**
- **They are generally highly persistent because of inductive effects of F and the 'poor leaving group' ability of F^-; Perfluorinated acids could 'redefine persistence';**
- **Breakage of C-F bonds requires specific conditions;**
- **Polyfluorinated compound are highly volatile with respect to mass;**
- **Longer chain Perfluorinated compounds are moderately bioaccumulative;**
- **Appropriate to treat acids such as PFOS, PFOA, etc as degradation products;**
- **Intermediates in the conversion of Fluoroalcohol to PFAcids are worth invesigation;**
- **As a first step in solving "the problem" address 'residual' materials;**
- **Chemical Architecture matters…watch out for large, perfluorinated chemicals that do not react with OH in the atmosphere ~ GWP issues.**

PolyFluoro Sulfamidoethanols....Big Picture



Finale...the FTOH Fate



Differences? More is known (published); potential for longer chain PFCAs from larger FTOHs.

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