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METHODS FOR OBTAINING FLUORINE-CONTAINING CARBOXYLIC ACIDS. COMMUNICATION 1

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Abstract: This part of the review deals with the following synthesis methods of fluorine-containing carboxylic acids: electrochemical fluorination (ECF), isomerization and anionic polymerization of perfluoroalkene oxides, and oligomerization of perfluoroalkenes in the liquid-phase oxidation processes.

Key words: electrochemical fluorination, perfluoroalkene oxides, perfluoroalkenes, liquid-phase oxidation, anionic polymerization.

Introduction

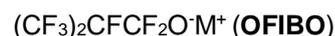
This review considers some synthesis methods of fluorine-containing carboxylic acids. Despite the fact that in recent years there has been a refusal of using perfluorinated aliphatic carboxylic acids as emulsifiers in the synthesis of fluorinated polymers and copolymers by aqueous emulsion polymerization, fluorine-containing carboxylic acids and their derivatives remain important precursors for the synthesis of various fluorinated materials.

In addition to the traditional fields of application (foaming agents, protective coatings, additives to lubricants, etc.) of fluorine-containing carboxylic acids and their derivatives, compounds of this class are used as additives to electrolytes in lithium-ion batteries (LIBs). This is necessary to improve the characteristics of such power sources at low temperatures [1]. Carboxylic acids are also used in the synthesis of biologically active compounds with fluorinated fragments, which can improve the physicochemical properties (acidity, lipophilicity, permeability) of pharmaceutical substances [2].

1. Electrochemical fluorination (ECF)

The ECF method is used to obtain perfluoroacyl fluorides, which are converted into the corresponding acids by hydrolysis. For a long time, the ECF method was one of the main industrial methods for obtaining these compounds.

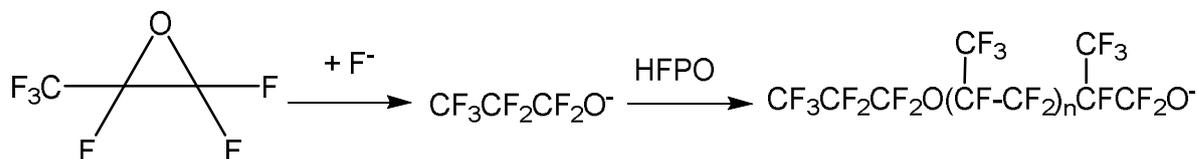
A number of nucleophilic fluorine-containing reagents are capable of opening the epoxide rings in alpha-oxides of perfluoroalkenes with a formation of perfluoroacyl fluorides. Thus, the presence of fluoride ions facilitates rapid opening of these rings while preserving the perfluorinated nature of the products. Nucleophilic attack occurs exclusively at the more substituted carbon with the formation of perfluoroalkoxides, which in some cases can be isolated from the reaction products [12]. As examples, the paper [12] provides alkoxides obtained from hexafluoropropylene oxides (HFPO) and octafluoro-isobutylene oxide (OFIBO).



Under the certain conditions, these salts lose M^+ and F^- fragments with a formation of the corresponding acyl fluorides. The latter can be converted to the acids by hydrolysis.

The nature of the fluoride ion and the nature of the M^+ ion play a very important role in the opening of epoxide ring and in the stability of the resulting perfluoroalkoxide. The authors of [12] conducted studies of more than 40 fluoride salts in various solvents and found that cesium fluoride in tetraglyme showed the best results.

The resulting alkoxides can further react with perfluoroalkene oxide molecules to produce oligomeric products (Scheme 4) [12].



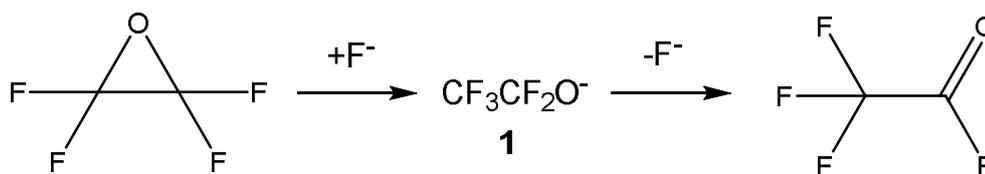
Scheme 4.

In addition, perfluoroalkene oxides can react with other fluorine-containing acyl fluorides and fluorine-containing ketones with a formation of the corresponding acyl fluorides.

The reactions of tetrafluoroethylene oxides (TFEO), hexafluoropropylene (HFPO) and some other perfluoroalkene oxides are covered in literary sources.

2.1.1. Isomerization and anionic polymerization of tetrafluoroethylene oxide (TFEO)

In 1966, the article by F. Gozzo and G. Camaggi reported the formation of trifluoroacetyl fluoride from tetrafluoroethylene oxide (TFEO) in the presence of potassium fluoride [13] (Scheme 5).



Scheme 5.

In 1967, V.I. Ginzburg and M.I. Vasilyeva also reported in their paper the rearrangement of TFEO into trifluoroacetyl fluoride in the presence of hydrogen fluoride even at $-78\text{ }^{\circ}\text{C}$ [14].

In the article by H. S. Eleuterio [15] it was reported that the rearrangement of TFEO to trifluoroacetyl fluoride can be carried out at room temperature on the catalyst surface or in the presence of fluoride ion (F^-) sources. In addition, it was noted that the reaction could spontaneously occur even at room temperature, therefore TFEO should be stored only at temperatures below the boiling point ($-65\text{ }^{\circ}\text{C}$).

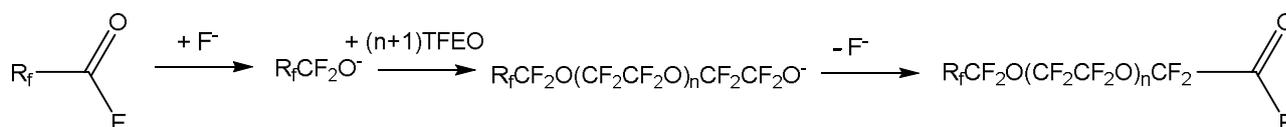
As noted above, the resulting alkoxide **1** (Scheme 5) can react further with perfluoroalkene oxide molecules to obtain the addition products.

Patent [16] gives an example of a reaction, which was carried out using activated carbon «Darco» as a catalyst at temperatures of $-52\div-30\text{ }^{\circ}\text{C}$. Perfluoroethoxyacetyl fluoride ($\text{CF}_2\text{CF}_2\text{-O-CF}_2\text{-C(O)F}$) and further addition products (trimer and tetramer of TFEO) were identified in the reaction products.

The resulting TFEO trimer could be hydrolyzed with water to the corresponding acid $\text{CF}_3\text{-CF}_2\text{-O-CF}_2\text{CF}_2\text{-O-CF}_2\text{-COOH}$ [16].

Other examples of obtaining TFEO polymer compounds are given in [17]. The process was carried out at low temperatures ($-70\div-80\text{ }^{\circ}\text{C}$) in the presence of catalysts. Tertiary amines (triethylamine, tributylamine, etc.) and divalent copper salts (Cu^{2+}) were used as catalysts. The products composition depended on the synthesis time: after 24 hours of synthesis, liquid compounds predominated in the products, after 48 hours of synthesis – solid compounds.

The patent [18] describes the addition reactions of TFEO in the presence of catalysts to other acyl fluorides: carbonyl fluoride, trifluoroacetyl fluoride, perfluoropropionyl fluoride, etc. The reactions were carried out in a medium of methylene chloride, dichloromethane, and various linear chlorofluorocarbons (Scheme 6).



Scheme 6. ($R_f = \text{F}, \text{CF}_3, \text{C}_2\text{F}_5$ et. Al., $n \geq 0$).

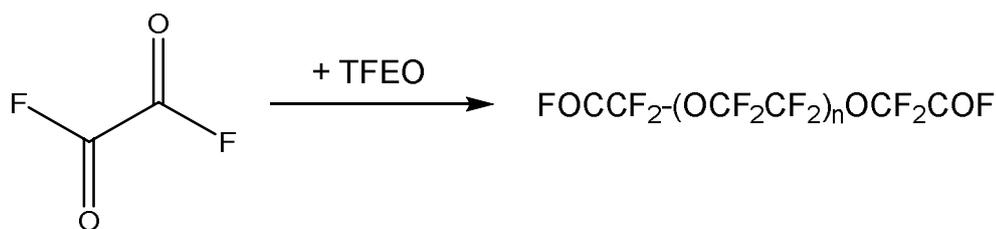
Tetraethylammonium cyanide or bromide were used as catalysts.

Thus, by reacting trifluoroacetyl fluoride (99 g) with TFEO (326 g) at a temperature of $-30\text{ }^{\circ}\text{C}$ and a pressure of $\approx 100\div 138\text{ kPa}$, the products presented in Table 1 were obtained (catalyst - tetraethylammonium cyanide) [18].

Table 1. The composition of reaction products of trifluoroacetyl fluoride with TFEO [18].

Structure	Mass, g	Boiling point, $^{\circ}\text{C}$
$\text{C}_2\text{F}_5\text{-O-CF}_2\text{COF}$	15	0-6
$\text{C}_2\text{F}_5\text{-O-C}_2\text{F}_4\text{-O-CF}_2\text{COF}$	69	65-67
$\text{C}_2\text{F}_5\text{-O-(C}_2\text{F}_4\text{-O)}_2\text{-CF}_2\text{COF}$	171	99-102
$\text{C}_2\text{F}_5\text{-O-(C}_2\text{F}_4\text{-O)}_3\text{-CF}_2\text{COF}$	103	134-138
$\text{C}_2\text{F}_5\text{-O-(C}_2\text{F}_4\text{-O)}_4\text{-CF}_2\text{COF}$	33	167-170

The reactions with fluorine-containing acyl fluorides of dibasic acids proceeded similarly. In this case, acyl fluorides containing simple ether bonds in the chain were obtained (Scheme 7) [14].



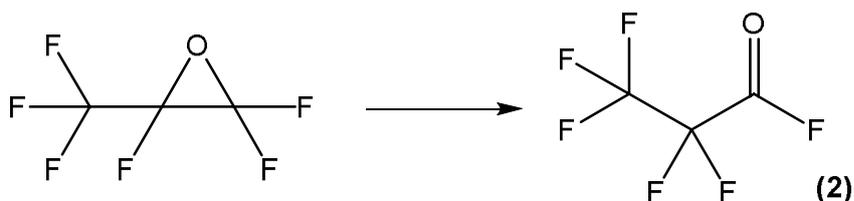
Scheme 7. ($n = 0\div 3$ [17]).

Perfluoroketones can also react with TFEO to produce the corresponding acyl fluorides. In [18], the reaction of hexafluoroacetone with TFEO to produce acyl fluorides of the general formula $(\text{CF}_3)_2\text{-CF-O-(C}_2\text{F}_4\text{-O)}_n\text{-CF}_2\text{COF}$ ($n=0\div 4$) with the predominant formation of $(\text{CF}_3)_2\text{-CF-O-CF}_2\text{COF}$ was described.

2.1.2. Isomerization and anionic polymerization of hexafluoropropylene oxide (HFPO)

The reactions of hexafluoropropylene oxide (HFPO) are much more well studied compared to TFEO. This is due to the fact that the methods for producing HFPO are more accessible. In addition, HFPO can withstand high temperatures up to $150\text{ }^{\circ}\text{C}$ inclusive [15].

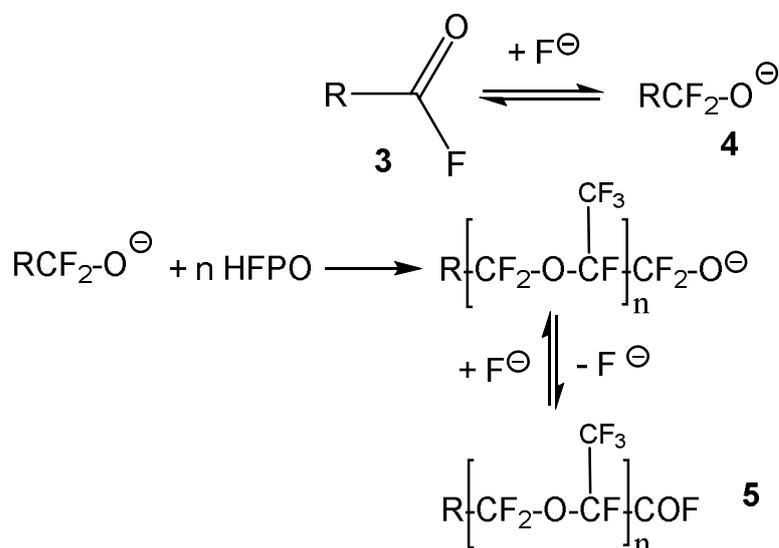
The process of isomerization of hexafluoropropylene oxide (HFPO) in reactions with nucleophilic agents with a formation of perfluoropropionyl fluoride (2) has been well studied (Scheme 8).

*Scheme 8.*

Various nucleophiles can be used to carry out this reaction, namely: primary, secondary and tertiary amines (in particular, triethylamine), Me_3SiOMe , $\text{Me}_2\text{Si}(\text{OEt})_2$ etc. [19].

There are different versions of the HFPO isomerization mechanism, which are discussed in [19-22].

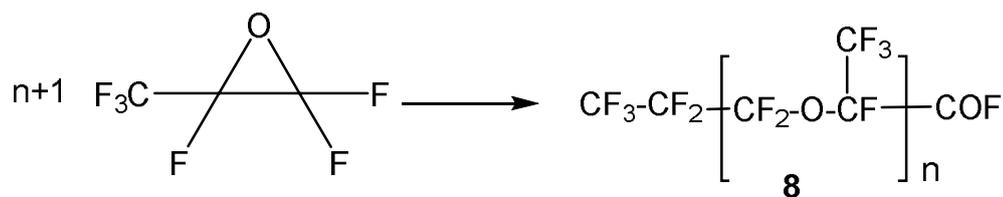
By reacting HFPO with primary acyl fluorides (**3**), the acyl fluorides of the general formula **5** (Scheme 9) can be obtained [19].

*Scheme 9.*

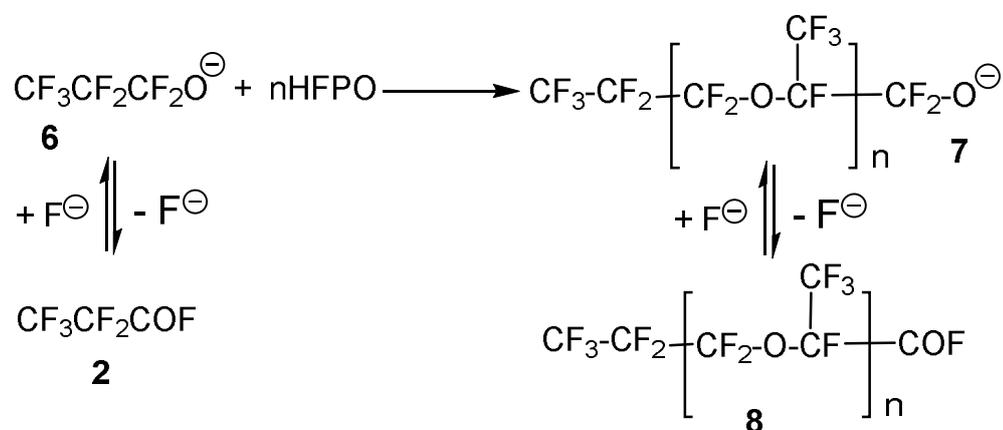
The starting acyl fluorides **3** can have different structures. The yield of the products of the general formula **5** depends on the nature of the radical **R** in acyl fluoride **3** and the stability of fluoroalkoxide **4**. A large number of references to examples of such reactions are given in [19].

The use of special catalytic systems promotes the formation of fluoroalkoxides **4**. In addition, the use of such catalysts should suppress the formation of perfluoropropionyl fluoride to prevent the side reaction of anionic polymerization of HFPO.

Anionic polymerization of HFPO is a special case of the interaction of HFPO with primary fluoroalkoxides and leads to the production of oligomeric acyl fluoride **8** with a number of $n=1\div 100$ (Scheme 10) [19].

*Scheme 10.*

The first step of this process is isomerization of HFPO to perfluoropropionyl fluoride (Scheme 4), which is in equilibrium with perfluoropropoxide ion **6** (Scheme 11). The latter attacks one HFPO molecule to form alkoxide **7** with $n=1$. In the next step, alkoxide **7** can further react with HFPO molecules to give alkoxides with $n>1$ or form acyl fluoride **8** after elimination of the fluoride ion [19].

*Scheme 11.*

The oligomerization degree depends on the catalyst system used, the reaction conditions and the purity of the starting HFPO [19].

Thus, when using tetramethyl thiourea ((Me₂N)₂CS) as a catalyst, a mixture of oligomers of the following composition was obtained in diglyme: 13% with $n = 1$, 40% with $n = 2$ and 22% with $n = 3$ [23].

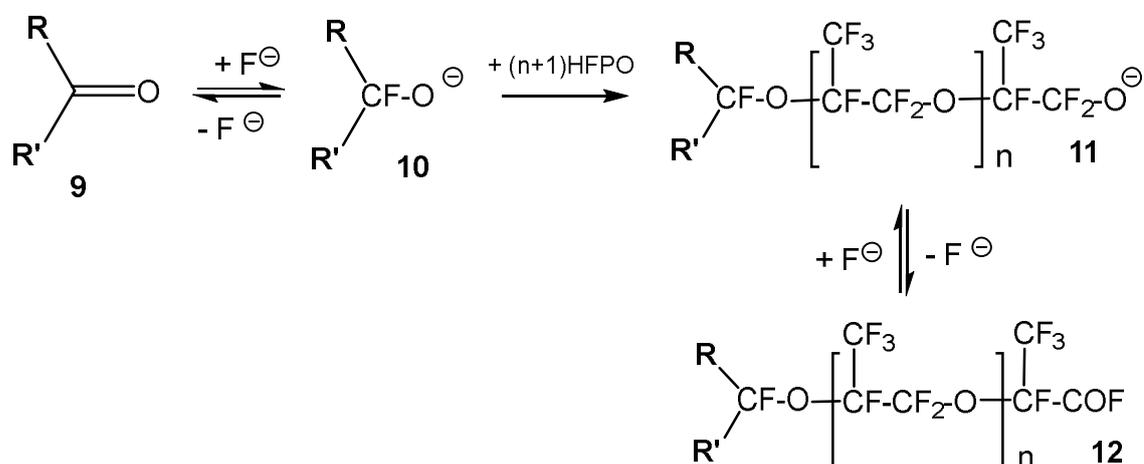
Table 2 shows examples of the dependence of the oligomerization degree of HFPO on the solvent nature [19].

Table 2. The dependence of the oligomerization degree of HFPO (n) on the solvent nature [19].

Solvent	Yield (%)				
	n=0	n=1	n=2	n=3	n=4
Tetrahydrofuran	100				
Acetonitrile	88	9	3		
Monoglym	71	20	9		

Diglym	32	31	25	10	
Tetraglym	16	17	21	20	10

The reactions of HFPO with fluorinated ketones can lead to the production of fluorinated acyl fluorides of the general formula **12** (Scheme 12) [19].

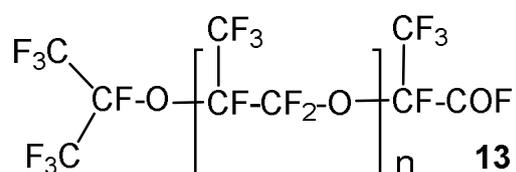


Scheme 12.

Secondary fluorinated alkoxides **10**, which are obtained in the presence of fluoride ions from fluorine-containing ketones **9**, as a result of interaction with HFPO form alkoxides of the general formula **11** (n=0). The further process proceeds either with the splitting off of fluoride ion with the formation of acyl fluoride **12** (n=0), or with the further addition of HFPO molecules to alkoxide **11** with the formation of acyl fluorides **12** (n≥1).

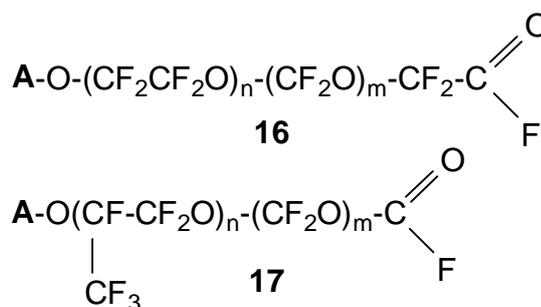
The patent [24] describes the reaction of HFPO with hexafluoroacetone (HFA), 1,3-dihydroperfluoroacetone, perfluoro-2-pentanone and a number of other perfluoroketones. The process conditions were as follows: initial temperature of -80 °C followed by heating to 80 °C, catalyst – cesium fluoride in diglyme. As a result of the reactions, the corresponding acyl fluorides of the general formula **12** were obtained.

In the case of the reaction of HFPO with HFA at a reagent ratio of 1:1, perfluoro-2-isopropoxypropionyl fluoride was predominantly obtained, from which the corresponding acid was obtained in the next step by hydrolysis. If the ratio of HFPO to HFA was 5:1, the compounds with n = 1-6 were found in reaction products **13**.



To remove the peroxide fragments (-O-O-), thermal treatment in the temperature range of 150÷300 °C, thermal stabilization with simultaneous UV irradiation [25] or chemical methods [32-34] are used.

As a result, oligomeric compounds **16** and **17** (Scheme 14) are obtained in most cases having at least one acyl fluoride group in their structure, which can be converted by hydrolysis into the corresponding acid.



Scheme 14.

By varying the process parameters (temperature, ratio of reactants, initiator nature, method of removing peroxide groups, etc.), the chain length of the resulting compounds and/or the preferred composition of the terminal groups can be adjusted.

For example, carrying out liquid-phase oxidation of HFP at a temperature of about -30 °C (initiator – F₂) led to a decrease in the molecular weight of oligomer **15** to MM ≈ 1000 [27], whereas carrying out the process at -50÷-60 °C leads to obtaining oligomer **15** with MM≈3000÷3500.

The paper [33] describes the production of peroxide PFPE by low-temperature liquid-phase oxidation of TFE (UV irradiation, T= - 40 °C, solvent R227ea) with the simultaneous addition of perfluoroacryloyl fluoride (CF₂=CF-COF) to the reactor. In this case, PFPE PO (MM≈2900) of the general formula X₁-O(CF₂O)_{n1}(CF₂CF₂O)_{m1}(CF₂(CF₂)_zCF₂O)_{p1}(O)_h-X₂ were obtained, where the groups X₁ and X₂ were -CF₂-COF or -COF. The destruction of peroxide bonds with 57% aqueous hydroiodic (HI) acid in the presence of methanol led to the formation of the products of the general formula Y₁-O(CF₂O)_{n1}(CF₂CF₂O)_{m1}(CF₂(CF₂)_zCF₂O)_{p1}-Y₂ with an average MM≈490, where Y₁ and Y₂ were the groups -CF₂COOCH₃ and/or -CF₂COOH.

The work [34] also describes the destruction of peroxide bonds in PO PFPE using a 57% aqueous solution of hydroiodic (HI) acid in the presence of methanol. However, the initial PO PFPE was obtained by low-temperature liquid-phase oxidation of TFE (initiator – F₂, T=-82 °C, solvent dichlorodifluoromethane) without additional ingredients. In this case, the products of the general formula Y-O(CF₂O)_a(CF₂CF₂O)_b-Y' with an average MM≈930 were obtained, where Y and Y' were the groups -CF₂COOCH₃, -CF₃, -C₂F₅ with a significant predominance of ester group.

The article [32] describes low-temperature liquid-phase oxidation of HFP, when, in addition to a monomer, oxygen, and an initiator, chlorotrifluoroethylene (CTFE) was introduced into the reactor as a «comonomer». As a result, polyether telomers of the general formula $\text{Cl}-(\text{C}_3\text{F}_6\text{O})_n-\text{CF}_2\text{CFO}$ were obtained. The resulting mixture could be separated into individual compounds by distillation. The obtained polyester telomers with a yield of more than 85% (weight) were converted into the corresponding carboxylic acids: $\text{Cl}-(\text{C}_3\text{F}_6\text{O})_n-\text{CF}_2\text{COOH}$, where $n=1\div 5$.

The process of obtaining polyether diacyl fluorides of the general formula **16** (group **A** was also predominantly acyl fluoride) is described in [35]. The initial peroxide PFPE **14** (Scheme 14), which was obtained by low-temperature liquid-phase oxidation of TFE with an average $\text{MM}\approx 83400$ and contained predominantly one acyl fluorides group, was treated with gaseous hydrogen in the presence of a catalyst (Pd/CaF_2) at a temperature of $125\div 130$ °C and a pressure of about 3 atm. The obtained diacyl fluorides did not contain peroxide bonds and had $\text{MM}\approx 1500$.

The papers [26,36] report on the production of the corresponding acids from acyl fluorides of the general formula **17** ($n=8\div 50$, $m=0\div 10$). They can then be used to obtain various surfactants.

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