On the formation and crystal structures of α,ω-perfluorodimorpholinoalkanes

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Abstract

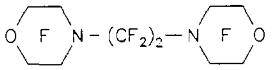
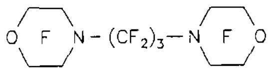
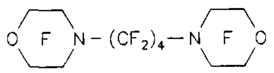
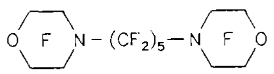
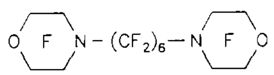
The results of the electrochemical fluorination (ECF) of α,ω-dimorpholinoalkanes with two to six CH_2 units between the morpholine rings are summarized. The crystal and molecular structures of the perfluorinated compounds are presented and discussed. Conclusions on the mechanism of electrochemical fluorination are drawn based on an ionic mechanism and a steric model.

Introduction

Since the pioneering work of Simons in the late 1940s, electrochemical fluorination (ECF) is one of the most common methods for manufacture of perfluorinated compounds. Several mechanisms have been suggested in order to explain this reaction. According to the one proposed by Simons [1], this process starts with the anodic oxidation of fluoride ions to radicals, which substitute the hydrogen atoms in the organic molecule after cleavage of the C–H bond. Other theories suggest that substitution of hydrogen atoms by fluorine atoms occurs by means of higher nickel fluorides [2] or through the adsorption on the anode of complexes of the organic compound with nickel fluorides [3]. An ionic mechanism for ECF was proposed by Meinert [4] in the 1960s and developed into a four-stage mechanism designated EC_bEC_N by Burdon *et al.* [5], Rozhkov [6] and Gambaretto and coworkers [7, 8]. The mechanism of ECF of derivatives of morpholine and piperidine has been discussed by Meinert *et al.* [9].

TABLE 1. Electrochemical fluorination of α,ω-dimorpholinoalkanes

$n = 2$–6

		Perfluorocarbon	Yield (%)	B.p. (°C)/ m.p. (°C)
1	$n = 2$		28	164/75.5
2	$n = 3$		44	182/56.0
3	$n = 4$		39	198/65.5
4	$n = 5$		43	215/60.0
5	$n = 6$		20	225/79.5

Results and discussion

Crystal structures

Our previously published results on the ECF of α,ω-dimorpholinoalkanes are summarized in Table 1 [9]. The perfluorinated α,ω-dimorpholinoalkanes were obtained as white solids in yields up to 44%. Melting points were between 55 °C and 80 °C.

The molecular structures of compounds **1** to **5** are shown in Fig. 1 along with the atomic labelling systems. These ORTEP plots and the projections (see Fig. 2) indicate that molecules with an even number of CF_2 units between the morpholine rings (**1**, **3** and **5**) have

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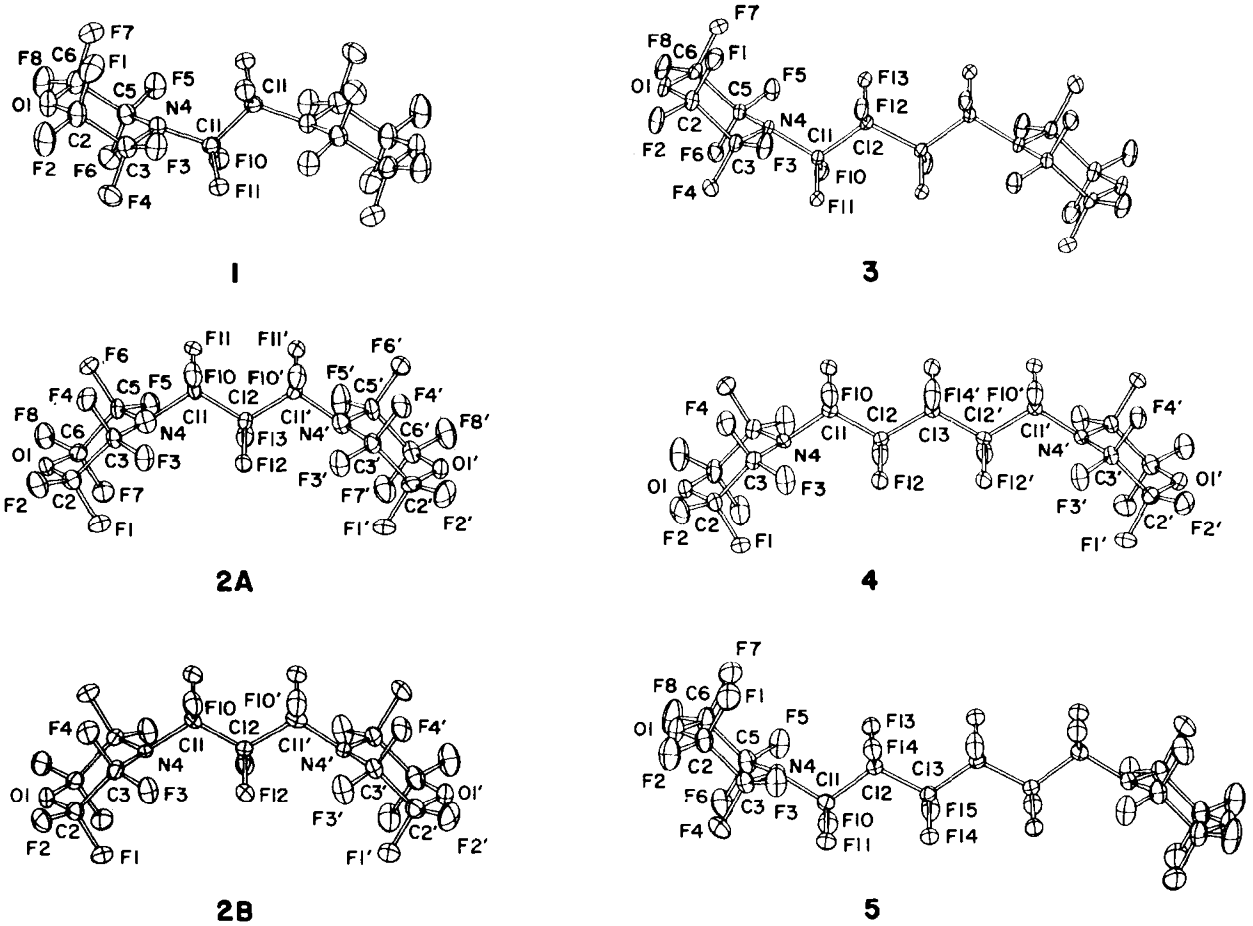

1 **3** **2A** **4** **2B** **5**

Fig. 1. ORTEP plots of compounds **1** to **5**. For compound **2** both independent molecules (A and B) are shown.

m/2 symmetry while molecules with an odd number of bridging CF_2 units (**2** and **4**) have *mm*2 symmetry. In the crystalline form, molecules of the first type have crystallographically imposed $\bar{1}$ symmetry while molecules of the second type crystallize in such a way that their ring-bisecting symmetry planes coincide with the crystallographic mirror planes. A molecule with no crystallographically imposed symmetry only occurs in **2** (molecule A), in addition to a molecule with crystallographic *m* symmetry (molecule B). In all five compounds the morpholine rings are in the chair conformation.

The packing of the molecules in the crystals is determined by their F···F intermolecular contacts. The shortest F···F contacts are 3.01 Å in **1**, 2.82 Å in **2**, 2.68 Å in **3**, 2.82 Å in **4** and 2.89 Å in **5**. The relatively short contact of 2.68 Å in **3** falls into the range of intramolecular contacts between F atoms which are not bonded at the same C atom. Evidently the van der Waals radius of 1.35 Å for fluorine reported by Pauling [10] represents a lower limit for intermolecular F···F contacts. For α-CF_4, a contact distance of 3.03 to 3.18 Å was found at 10 K [11].

The bond distances and angles for compounds **1** to **5** are listed in Table 2. A comparison of the geometric parameters of the perfluorinated morpholine ring with its H analogue in bis(morpholino) disulphide [12] indicates that fluorination causes a lengthening of the C—C bonds by *c*. 0.02 Å and a shortening of the C—O and C—N bonds by *c*. 0.03 Å and 0.02 Å, respectively. A slight increase in the average C—C bond lengths upon fluorination is also observed for the $(CF_2)_n$ chains in our compounds (C—C in ethane [13], 1.533(2) Å; mean value for **1**, **3**, **4** and **5** from Table 2, 1.548 ± 0.012 Å*). This agrees with observations for other pairs of C_nH_m and C_nF_m compounds; see, for example, ref. 14. According to Table 3, all ring angles in the fluorinated compounds are larger than the corresponding angles in the H analogue. This means that fluorination effects a flattening of the morpholine ring. As a simple measure for this effect, the deviation of the sum of the ring angles from 720° (the sum for a planar six-membered ring) can be used: the sums for our compounds are

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*Compound **2** is not included here nor in the following discussion because of the relatively high scatter of its distances and angles.

TABLE 2. Bond lengths (Å) and angles (°) for compounds **1** to **5**[a]

	Compound **1**	Compound **2**				Compound **3**	Compound **4**		Compound **5**
		Molecule A; symmetry 1		Molecule B; symmetry *m*					
(a) Bond lengths (Å)									
O(1)–C(2)	1.378(2)	1.346(10)	1.387(11)	1.359(10)	1.383(11)	1.377(3)	1.372(7)	1.364(6)	1.374(5)
O(1)–C(6)	1.379(2)	1.399(10)	1.322(11)	=	=	1.389(3)	=	=	1.371(6)
N(4)–C(3)	1.446(2)	1.443(9)	1.446(10)	1.461(9)	1.443(10)	1.444(3)	1.438(6)	1.442(5)	1.447(5)
N(4)–C(5)	1.443(2)	1.433(10)	1.447(10)	=	=	1.444(3)	–	–	1.435(5)
N(4)–C(11)	1.467(2)	1.499(10)	1.486(10)	1.467(8)	1.462(10)	1.476(3)	1.456(6)	1.460(5)	1.458(4)
C(2)–C(3)	1.541(3)	1.584(11)	1.538(12)	1.537(12)	1.541(13)	1.546(4)	1.529(8)	1.533(7)	1.528(6)
C(5)–C(6)	1.545(2)	1.542(11)	1.547(12)	=	=	1.548(4)	–	–	1.529(6)
C(11)–C(11)′	1.549(3)	–	–	–	–	–	–	–	–
C(11)–C(12)	–	1.556(11)	1.513(11)	1.519(10)	1.529(11)	1.562(4)	1.558(6)	1.557(5)	1.544(5)
C(12)–C(12)′	–	–	–	–	–	1.546(5)	–	–	–
C(12)–C(13)	–	–	–	–	–	–	1.537(6)	1.536(5)	1.561(4)
C(13)–C(13)′	–	–	–	–	–	–	–	–	1.527(5)
C(2)–F(1)	1.336(2)	1.343(10)	1.330(11)	1.357(10)	1.342(11)	1.339(3)	1.322(8)	1.343(6)	1.331(5)
C(2)–F(2)	1.320(2)	1.308(10)	1.326(11)	1.309(10)	1.312(11)	1.333(3)	1.326(7)	1.323(6)	1.310(5)
C(3)–F(3)	1.332(2)	1.320(9)	1.341(10)	1.311(9)	1.309(10)	1.335(3)	1.329(6)	1.333(6)	1.333(5)
C(3)–F(4)	1.347(2)	1.342(9)	1.348(9)	1.332(10)	1.365(10)	1.349(3)	1.340(6)	1.344(5)	1.337(5)
C(5)–F(5)	1.335(2)	1.334(9)	1.324(10)	=	=	1.336(3)	–	–	1.338(5)
C(5)–F(6)	1.344(2)	1.354(9)	1.358(10)	=	=	1.348(3)	–	–	1.344(5)
C(6)–F(7)	1.331(2)	1.294(10)	1.328(10)	=	=	1.335(3)	–	–	1.331(6)
C(6)–F(8)	1.319(2)	1.326(10)	1.339(10)	=	=	1.326(3)	–	–	1.317(6)
C(chain)–F									
min.	1.337(2)	1.313(10)				1.339(3)	1.320(6)		1.327(4)
max.	1.338(2)	1.352(8)				1.341(3)	1.331(5)		1.349(4)
(b) Angles (°)									
C–O(1)–C	115.9(1)	116.5(6)	113.9(7)	116.5(6)	114.0(7)	114.8(2)	114.6(4)	114.6(4)	114.9(3)
O–C(2)–C	113.1(2)	113.2(7)	112.7(7)	115.1(7)	114.4(7)	113.3(2)	114.1(5)	114.6(4)	113.2(3)
C–C(3)–N	111.0(1)	109.8(6)	111.3(7)	109.7(6)	111.1(7)	110.9(2)	111.3(4)	111.4(4)	111.6(3)
C(3)–N(4)–C(5)	114.9(1)	116.2(6)	113.7(6)	116.5(5)	116.2(6)	114.7(2)	114.5(3)	114.4(3)	113.6(3)
C(3)–N(4)–C(11)	117.8(1)	117.2(6)	119.0(6)	117.2(5)	117.3(6)	117.6(2)	118.1(3)	118.2(3)	118.5(3)
C(5)–N(4)–C(11)	117.9(1)	116.8(6)	117.3(6)	=	=	117.5(2)	=	=	118.8(3)
N–C(5)–C	111.3(1)	110.7(6)	110.2(6)	=	=	111.3(2)	=	=	111.8(3)
C–C(6)–O	112.7(1)	111.3(7)	115.1(7)	=	=	112.8(2)	=	=	113.3(4)
N–C(11)–C	111.3(2)	111.5(6)	110.6(6)	113.9(5)	113.0(6)	110.8(2)	112.8(3)	111.8(3)	111.5(3)
C–C(12)–C	–	113.3(6)	=	117.6(6)	=	115.4(2)	115.9(3)	115.6(3)	114.9(3)
C–C(13)–C	–	–	–	–	–	–	116.1(3)	=	114.3(3)
F–C(2)–F	108.4(2)	108.2(7)	108.6(7)	106.4(6)	108.2(8)	108.1(2)	107.9(5)	107.9(4)	107.8(4)
F–C(3)–F	107.8(1)	108.2(6)	106.8(6)	108.1(6)	107.8(7)	108.1(2)	108.1(4)	108.0(4)	107.0(3)
F–C(5)–F	107.6(1)	108.5(6)	107.0(6)	=	=	107.8(2)	=	=	107.2(3)
F–C(6)–F	108.7(2)	109.6(7)	106.6(7)	=	=	108.9(2)	=	=	107.1(4)
F–C(11)–F	107.8(1)	107.8(6)	106.7(6)	104.2(6)	105.6(7)	107.8(2)	106.1(3)	107.0(3)	106.8(3)
F–C(12)–F	–	107.3(6)	=	105.7(5)	=	108.6(2)	108.3(3)	107.2(3)	108.4(3)
F–C(13)–F	–	–	–	–	–	–	106.7(4)	=	108.0(3)

[a] For compounds **2** and **4**, the left-hand columns refer to the unprimed and the right-hand columns to the primed atoms. For **1**, **3** and **5**, only one column appears because of the crystallographic $\bar{1}$ symmetry. A '–' entry indicates that the corresponding atom numbers do not exist in the molecule; a '=' entry indicates that the corresponding distance or angle is equal by crystallographic symmetry to one already given.

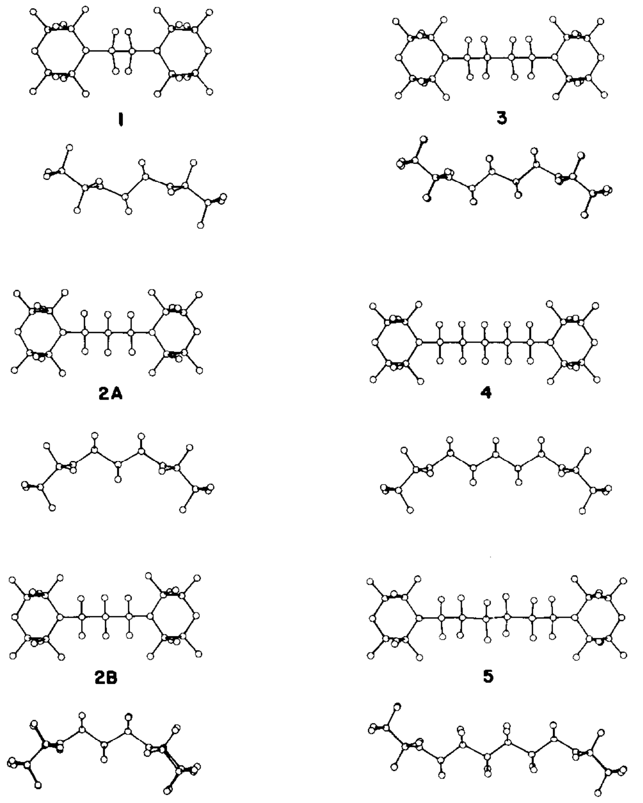

Fig. 2. Projections for the molecules of compounds **1** to **5**. For each drawing, the N−N vector lies in the projection plane. The first drawing of a molecule has its C(3)−C(5) vector parallel to the drawing plane. In the second drawing, the molecule is rotated about its N−N vector by 90°.

TABLE 3. Comparison of compounds **1**, **3**, **4** and **5**, and bis(morpholino) disulphide with respect to bond lengths (Å) and angles (°) in the morpholine ring

	Compounds **1**, **3**, **4** and **5**		Bis(morpholino) disulphide [12]	
	Minimum	Maximum	Minimum	Maximum
C–C	1.528(6)	1.548(4)	1.498(6)	1.513(6)
C–O	1.364(6)	1.389(3)	1.402(6)	1.419(5)
C–N	1.435(5)	1.447(2)	1.445(5)	1.470(5)
C–O–C	114.6(4)	115.9(1)	109.8(4)	110.3(3)
O–C–C	113.1(2)	114.6(4)	111.1(4)	112.0(4)
C–C–N	110.9(2)	111.6(3)	108.9(3)	109.6(3)
C–N–C	113.6(3)	114.9(1)	110.9(2)	111.2(3)

678.9° (**1**), 677.8° (**3**), 679.9° and 681.0° (**4**), 678.4° (**5**), and for the rings in bis(morpholino) disulphide [12] they are 662.7° and 662.4°.

Similarly, the geometry of the NC(3)−C(5)−C(11) groups in **1** to **5** deviates less from planarity than in bis(morpholino) disulphide: 350.6° (**1**), 349.8° (**3**), 350.7° and 350.8° (**4**), 350.9° (**5**), 343.2° and 344.1° (bis(morpholino) disulphide [12]).

Formation mechanism

Our concept of electrofluorination of organic compounds is based on the assumption that the first step is the anodic oxidation of the part of a molecule with the lowest oxidation potential [4]. The process of ECF is promoted by a weakening of C−H bonds due to hydrogen–fluorine bridges. After anodic withdrawal, the C−F bond is formed by insertion of a fluoride ion present in the Helmholtz double layer at the surface of the electrode (Fig. 3). Formation of the C−F bond promotes an electrofugal departure of further hydrogen atoms at this carbon atom through weakening of the C−H bonds. This hydrogen–fluorine exchange is repeated until the whole molecule is perfluorinated. After perfluorination the molecule leaves the adsorption layer at the anode and moves into the bath. This mechanism was subsequently developed to the EC_bEC_N mechanism by Burdon *et al.* [5], Rozhkov [6] and Gambaretto and coworkers [7, 8]. Figure 4 shows the two possibilities for the introduction of the first fluorine atom into a morpholine molecule as given by Gambaretto and coworkers [7]. In our molecules the introduction of the first fluorine atom can occur according to the two ways shown in Fig. 4. In the case of *N*-methylmorpholine, the reaction evidently proceeds by the first route.

According to our concept, the initial anodic oxidation of the compound to be fluorinated is a normal part of electrofluorination. This means that the substitution of hydrogen atoms by fluorine atoms does not occur randomly (as it should do if a radical mechanism is operating), but proceeds in a selective way, starting at the carbon atom most easily oxidized. We improved our ECF mechanism by consideration of the steric arrangement of molecules in the Helmholtz layer. Based on the molecular structures of α,ω-dimorpholinoalkanes, it can be assumed that the perfluorinated and partially fluorinated molecules have, at least, a similar shape.

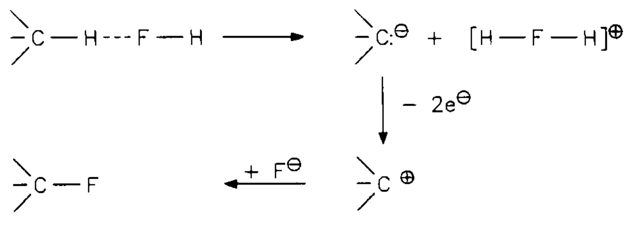

Fig. 3. Mechanism of substitution of the first hydrogen atom by a fluorine atom during electrochemical fluorination.

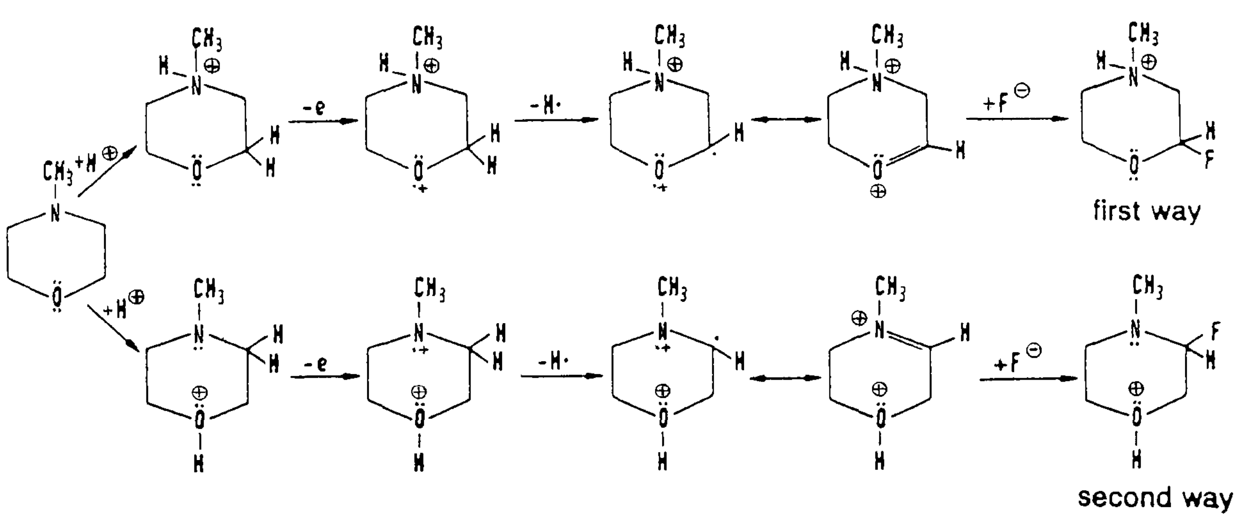

Fig. 4. Possible mechanisms for the introduction of the first fluorine atom in the *N*-methylmorpholine molecule [7].

So the hydrogen-containing starting material will be inserted in the double layer of the anode as shown in Fig. 5. The marked positions reach the anode and will be fluorinated first. In the case of **2** and **4**, ECF will start near the oxygen atoms of the morpholine ring in accordance with previously published results [7, 9]. In the case of **1**, **3** and **5**, ECF can start in the same molecule α to an oxygen atom or α to a nitrogen atom. In these cases, routes 1 and 2 are possible for the start of ECF.

These results provide further evidence that ECF proceeds via an ionic mechanism as opposed to a radical mechanism. ECF starts at the position most easily oxidized, i.e. in the case of morpholines the position adjacent to the heteroatoms. Whether ECF starts adjacent to oxygen or nitrogen is determined solely by the geometry of insertion of the molecule in the surface of the anode. In the case of α,ω-dimorpholinoalkanes, a favourable insertion in the anode occurs resulting in high yields of greater than 40%.

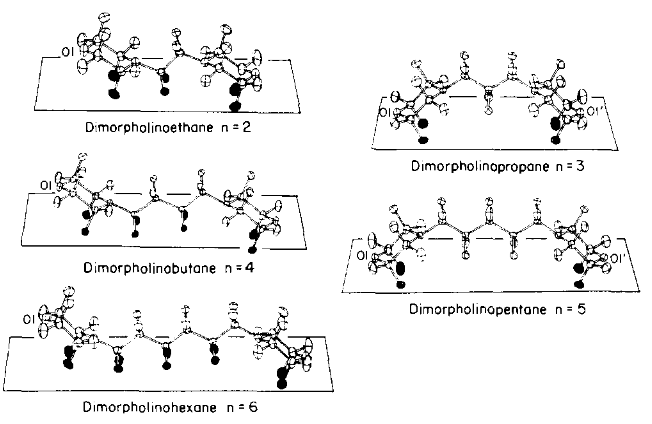

Fig. 5. Assumed insertion of dimorpholinoalkanes in the surface of the anode at the beginning of electrochemical fluorination. The dark hydrogen atoms are those nearest to the anode and will be fluorinated first.

Experimental

The synthesis and characterization of the *F*-dimorphoalinoalkanes **1–5** has been described elsewhere [9].

X-Ray crystallography

Crystal fragments of all five compounds were sealed in Lindemann glass capillaries to prevent sublimation. All X-ray measurements were carried out at room temperature on a Philips PW 1100 diffractometer with graphite-monochromated Mo Kα radiation ($\lambda = 0.71069$ Å). Intensity data were collected in the conventional $\theta/2\theta$ scan mode. The structures were solved by Direct Methods [15, 16] and refined via standard least-squares and Fourier techniques [17]. Crystal data, data collection parameters and structure refinement details are listed in Table 4. The atomic parameters and consequently the bond distances and angles of compound **2** have relatively high standard deviations. This results from partial overlap of X-ray reflexions which in turn is a consequence of the one large lattice constant ($b = 37.486(13)$ Å).

Additional data concerning these structure determinations (lists of positional and thermal atomic parameters, F_o/F_c values) are available on request from the Fachinformationszentrum Energie, Physik, Mathematik, D-7514 Eggenstein–Leopoldshafen 2, quoting the registry No. CSD 57501, the names of the authors and the journal citation.

TABLE 4. Crystallographic data for α,ω-perfluorodimorpholinoalkanes

	Compound 1	Compound 2	Compound 3	Compound 4	Compound 5
Chemical formula	$C_{10}F_{20}N_2O_2$	$C_{11}F_{22}N_2O_2$	$C_{12}F_{24}N_2O_2$	$C_{13}F_{26}N_2O_2$	$C_{14}F_{28}N_2O_2$
M_r (g mol^{-1})	560.09	610.10	660.10	710.11	760.12
Crystal system	triclinic	orthorhombic	monoclinic	orthorhombic	triclinic
Space group	$P\bar{1}$ (No. 2)	*Pnma* (No. 62)	$P2_1/n$ (No. 14)	*Pnma* (No. 62)	$P\bar{1}$ (No. 2)
a (Å)	5.656(1)	11.734(4)	10.475(5)	11.556(2)	5.965(1)
b (Å)	7.061(1)	37.486(13)	11.011(6)	12.062(2)	8.276(2)
c (Å)	11.396(2)	12.365(6)	8.222(5)	15.105(2)	11.700(3)
α (°)	101.18(2)	90	90	90	104.15(2)
β (°)	95.99(2)	90	95.01(5)	90	92.21(2)
γ (°)	113.44(1)	90	90	90	92.62(2)
Z	1	12	2	4	1
V (Å^3)	401.2	5438.9	944.7	2105.5	558.7
$d_{calc.}$ (g cm^{-3})	2.318	2.235	2.320	2.240	2.259
μ(Mo Kα) (cm^{-1})	2.4	2.3	2.4	2.3	2.3
F(000) (e)	270	3528	636	1368	366
ν_{max} (°)	25	23	25	25	25
hkl range	±6, ±8, +13	+12, +41, +13	±12, +13, +9	+13, +14, ±17	±7, +9, ±13
Measured refl.	1504	3557	1787	3806	2158
Unique refl.	1389	3557	1666	1928	1858
Observed refl.	1389	2767 $[F_o \geqslant 3\sigma(F_o)]$	1412 $[F_o \geqslant 2.5\sigma(F_o)]$	1700 $[F_o \geqslant 3\sigma(F_o)]$	1626 $[F_o \geqslant 3\sigma(F_o)]$
Refined parameters	154	511	181	208	208
R	0.042	0.088	0.045	0.079	0.066
$R_w(F)$	0.057	0.107	0.047	0.106	0.085
$\Delta\rho$ (max./min.) (e Å^{-3})	+0.23/−0.32	+0.45/−0.57	+0.29/−0.37	+0.54/−0.36	+0.31/−0.41

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