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Successful Direct Fluorination of Oxygen-Containing Hydrocarbons

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New methods which have been recently developed for direct fluorination have enabled practical syntheses in high yields of oxygen-containing perfluorocarbons from their hydrocarbon analogs. These syntheses have been successful on several important classes of oxygen-containing hydrocarbons and most functional groups survive these gentle fluorinations. The syntheses of perfluoro-1,2-dimethoxyethane, perfluorobis(2-methoxyethyl) ether, perfluoro-1,2-diethoxyethane, perfluoro-1,4-dioxane, perfluoroethyl acetate, perfluorodimethylmalonyl difluoride, and perfluoropivaloyl fluoride from their hydrocarbon analogs are discussed. The monohydro species α-hydrotetrafluoroethyl trifluoroacetate, monohydroctafluoropivaloyl fluoride, and 1-hydrononafluoro-2,5-dioxahexane have also been prepared and characterized.

A substantial body of oxygen-containing and functional perfluoroorganic compounds have been prepared and characterized over the last 30 years and their physical properties investigated. Some have been prepared by fluorination using fluorinating agents such as cobalt trifluoride, but the majority have been prepared by the industrially important hydrogen fluoride electrochemical cell techniques pioneered by Simons.[1b] Relatively few successful syntheses of such species have been reported using elemental fluorine as the fluorinating agent. For example: "Fluorination by fluorine is unlikely to be used in normal organic syntheses".[2] A new technique for direct fluorination developed by Lagow and Margrave[3] has led to practical methods[4-7] for the synthesis of oxygen-containing perfluorocarbons from their hydrocarbon analogs. These new direct fluorination techniques for preparing functional and oxygen-containing fluorocarbons promise to develop into an important synthetic method yielding many unreported fluorocarbon compounds and better syntheses for many known compounds. In addition, direct fluorination is particularly valuable for preparing fluorocarbon compounds which are impossible or difficult to obtain by methods such as the cobalt trifluoride or electrochemical methods. The use of direct fluorination to prepare fluorocarbon species such as esters and some ethers whose hydrocarbon analogs are spontaneously decomposed in the hydrogen fluoride solvent used in the electrochemical cell establishes that there are many unique applications for such synthetic techniques.

Several new fluorocarbon compounds which are perfluoro analogs of structurally basic hydrocarbon species are reported in this paper (see Figure 1). Every synthesis reported in this paper represents the highest yield of perfluoro analog yet obtained with any method involving fluorination of the respective starting materials. The yields obtained for the present syntheses of perfluoro-1,4-dioxane, perfluoro-1,2-dimethoxyethane, perfluorobis(2-methoxyethyl) ether, perfluoro-1,2-diethoxyethane, perfluorodimethylmalonyl difluoride, and perfluoropivaloyl fluoride are the highest obtained by any synthetic method.

Experimental Section

Mass spectra were measured on a Hitachi RMU6B mass spectrometer at 70 eV. NMR spectra were taken on a Perkin-Elmer R20-B spectrometer at 70 MHz for protons and 56.466 MHz for fluorine. Gas chromatography separations were made using either a Varian Moduline 2700 or a Bendix Model 2300 gas chromatograph. Either a 10% SE-30 or Chromosorb P on a fluorosilicone QF1-0065 10% on Chromosorb P column (10 m × 0.375 in.) was used; however, the fluorosilicone column generally provided better separation.

Molecular weight determinations were performed on 20–50-mg samples sealed in preweighed capillaries and broken into a 66-cm^3 bulb attached to a manometer calibrated for volume change with pressure. Precision was about 0.5%.

Carbon, hydrogen, and fluorine analyses were done by Schwarzkopf Microanalytical Laboratory on 4–10-mg samples sealed under nitrogen into preweighed capillaries. Precision using this technique usually was 0.2–0.3% for fluorine analyses.

The reactor system used is illustrated in Figure 2, except that for the fluorination of pivaloyl fluoride and dimethylmalonyl difluoride a six-zone cryogenic reactor was used. The dimensions of the reactor have been previously described.[4] Physical properties of reactants are important in the cryogenic fluorination reactor. An ideal compound should have a reasonably high vapor pressure in the solid state. The combination of volatility and exposure in the solid phase, except during transfer, permits the renewal of the reactant surface as the more volatile products are produced and the dissipation of heat into the lattice and ultimately to the supporting copper turnings, walls, and cooling system in the reactor. A large initial surface area formed by sublimation of the reactant into the reactor permits fluorine at very low concentrations (less than 2%) to react with a large percentage of the hydrocarbon molecules.

Initial fluorination of a hydrocarbon decreases the volatility of the species. At about 50% fluorination, a maximum boiling point or minimum vapor pressure occurs. Under such conditions, hydrogen bonding and other associative interactions are at a maximum. After such a minimum vapor pressure of the reactant is obtained, each successive substitution of a fluorine for a hydrogen atom increases the vapor pressure. If at this point a temperature gradient is produced in the reactor, the more highly fluorinated products will be volatilized, exposing less highly fluorinated, less volatile species to interaction with fluorine. By repeating the above procedure, essentially complete fluorination of the hydrocarbon can occur under conditions which maintain a slow controllable rate of reaction. In the initial stages of the reaction, this rate of reaction is controlled by a high dilution of the fluorine and by cryogenic temperatures which reduce the reaction rate. As the reaction proceeds and more protons have been replaced by fluorine, the concentration of fluorine is increased and the temperature gradient applied to maintain a more constant rate of reaction. The amount of fluorine used is carefully controlled and is usually between 30 and 150 mmol/day. Should combustion occur, all the fluorine in the reactor is consumed and the reaction terminates until more fluorine is delivered. Therefore, the only adverse effect is an unsuccessful reaction. This is an important safety factor.

Perfluoro-1,2-dimethoxyethane. 1,2-Dimethoxyethane (4.015

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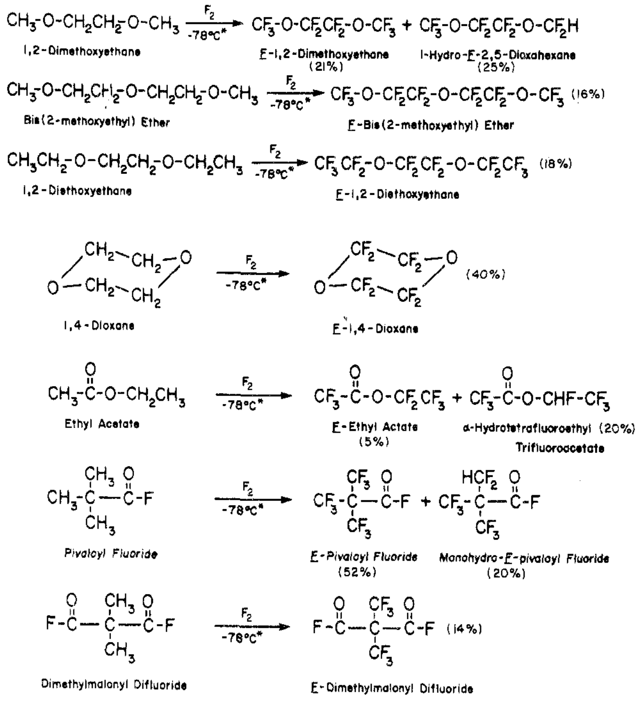


*Coldest Temperature of Gradient

Figure 1. Direct fluorination of oxygen-containing hydrocarbons.

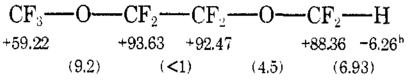
g, 0.045 mol) was evaporated employing a flow of 50–100 cm^3 of helium into a gradient reactor containing four distinct zones which were maintained at −78°, a temperature below the freezing point of the ether (−58°). An initial flow of 0.5 cm^3/min fluorine and 20 cm^3/min helium was started and after 12 hr the fluorine was increased to 1.0 cm^3/min. After an additional 12 hr, zone 1 was allowed to run out of Dry Ice. Twelve hours after zone 1 was clear of Dry Ice the fluorine was increased to 1.5 cm^3/min while still maintaining helium flow at 20 cm^3/min. The fluorine flow was maintained at 1.5 cm^3/min. On alternate days the helium was reduced to 10 cm^3/min followed by allowing one additional zone to clear of Dry Ice. Subsequent reductions to 5, then to 0 cm^3/min helium flow were followed each time by warming of one additional zone.[8] Finally, as the reactor warmed under a flow of pure fluorine, the fluorinated ether was passed through a metal trap filled with sodium fluoride pellets and into a glass trap maintained at −78°. The raw fluorocarbon ethers collected represented a mass which corresponds to between 50 and 100% of the expected yield based on moles of the parent ether. This mixture contained several hydrofluoro ethers and other hydrolytically unstable and corrosive products along with a smaller amount of perfluorinated fragments. In earlier work with the four-zone reactor, the yield of the hydrofluoro ethers in most cases exceeded the yield of perfluoro ethers owing to incomplete reaction. These products were removed by aqueous alkali hydrolysis and the hydrolytically stable ethers fractionated. The bulk of the desired products was collected in the −95 and −130° traps (combined weight 2.48 g, 20.6%). Final purification was accomplished using gas–liquid chromatography using a 0.375-in. fluorosilicone (QF-1-0065, 10% on Chromosorb P, 60/30 mesh) column.

Perfluoro-1,2-dimethoxyethane is a gas at room temperature (bp 16.7°). The molecular weight determined by the ideal gas method was 269 (cf. 270 for $C_4F_{10}O_2$). The ^{19}F NMR consisted of a triplet at +59.54 ppm and a quartet at +94.19 ppm relative to $CFCl_3$[9] with coupling constant 9.2 Hz and relative intensities 3:2. The infrared spectrum exhibited bands at 1410 (w), 1295 (s), 1250 (s), 1200 (w), 1170 (sh), 1155 (s), 1105 (w), 923 (w), 887 (m), 865 (w), 819 (w), and 690 cm^{-1} (w). The mass spectrum contained no parent peak but showed strong peaks at m/e 135 corresponding to the symmetrical cleavage of the molecule (CF_3-O-CF_2). Other strong peaks were m/e 119, C_2F_5; 100, C_2F_4; 69, CF_3; 50, CF_2; and 47, CFO. The yield was 21%.

Anal. Calcd for $C_4F_{10}O_2$: C, 17.79; F, 70.36. Found: C, 17.41; F, 70.08.

1-Hydrononafluoro-2,5-dioxahexane. If the products of the previously described reaction were not hydrolyzed, a second major product may be isolated which in some cases exceeds the amount of perfluoro-1,2-dimethoxyethane. This ether was a liquid with a disagreeable odor and may be quite toxic. Its molecular weight was determined to be 251 (cf. 252 for $C_4HF_9O_2$). Its ^{19}F NMR spectrum exhibited a triplet at +59.22 ppm and a quartet at +93.63 ppm with a coupling constant of 9.4 Hz and relative intensity of 2:2 respectively: a doublet centered at +88.36 (J = 70.0 Hz) split into triplets (J = 4.4 Hz) and a triplet at +92.47 ppm (J = 4.6 Hz) relative to $CFCl_3$ with relative integrals of 2:2. The proton NMR consisted of a triplet at −6.26 ppm relative to external Me_4Si, with coupling constant equal to 68.6 Hz in good agreement with the doublet splitting in the ^{19}F NMR. If the proton was irradiated the ^{19}F doublet decayed into a singlet. This information is consistent with a structure containing a proton in the α position (Chart I).

Chart I
1-Hydrononafluoro-2,5-dioxahexane



$$\begin{array}{ccccccc} CF_3 & — O — & CF_2 & — CF_2 & — O — & CF_2 & — H \\ +59.22 & & +93.63 & +92.47 & & +88.36 & -6.26^{b} \\ & (9.2) & & (<1) & (4.5) & (6.93) & \end{array}$$

The mass spectrum supports this conclusion. The two peaks corresponding to "symmetrical" cleavage at m/e 135, C_2F_5O, and m/e 117, C_2HF_4O, were both strong with relative intensities of 1:1.5, respectively, as are the very strong peaks at m/e 69, CF_3, and m/e 51, CHF_2, of relative intensities 1:1.5. Other, less intense peaks support this conclusion.

The infrared spectrum contains a weak proton absorption at 3028 cm^{-1} in addition to carbon–fluorine and carbon–oxygen bands at 1400 (w, br), 1370 (w), 1295 (s), 1250 (s), 1192 (m), 1179 (sh), 1159 (s), 1125 (s), 1040 (m), 910 (m), 853 (w), 818 (m), 700 cm^{-1} (w). The yield was 0–25%.

Perfluorobis(2-methoxyethyl) Ether. Bis(2-methoxyethyl) ether (1.79 g, 0.0134 mol) was evaporated at 50° into the four-zone cryogenic reactor (zone 1, −40°; zones 2–4 at −78°) using a 80–100 cm^3/min flow of helium gas. After 6–8 hr the helium flow was reduced to 20 cm^3/min and a 0.5 cm^3/min flow of fluorine was started. A similar procedure to that used for 1,2-dimethoxyethane was used to complete the reaction. The raw products were fractionated through −63, −78, −95, and −196° traps. Perfluorobis(2-methoxyethyl) ether was collected from the −78 and −95° traps (yield 0.83 g, 16.1%). Perfluorobis(2-methoxyethyl) ether is a volatile liquid, bp 60–63°. Its molecular weight was determined to be 385 (cf. 386 for $C_6F_{14}O_3$). The ^{19}F NMR exhibited a triplet at +59.30 ppm and a quartet at +92.84 ppm (J = 9.4 Hz) and a singlet at +91.61 ppm relative to $CFCl_3$. The relative integrals of the absorptions were 3:2:2, respectively.

The infrared spectrum contained bands at 1385 (w), 1295 (s), 1250 (s), 1220 (sh, w), 1200 (w), 1165 (s), 1145 (s), 920 (sh), 910 (m), 770 (m), 697 (w), and 681 cm^{-1} (sh).

The mass spectrum contained strong peaks at m/e 185, C_3F_7O; 135, C_2F_5O; 119, C_2F_5; 100, C_2F_4; 69, CF_3; and 50, CF_2. The yield was 16%.

Anal. Calcd for $C_6F_{14}O_3$: C, 18.67; F, 68.90. Found: C, 18.64; F, 69.94.

Perfluoro-1,2-diethoxyethane. A 1.81-g (0.0153 mol) sample of 1,2-diethoxyethane was injected into the evaporator of a cryogenic reactor.[4] The sample was evaporated into the reactor (Z_1 = −30, Z_2 = −50, Z_4 = −78°) using a 175 cm^3/min flow of helium. After 17 hr, zones 1–4 were cooled to −78°, the helium flow was reduced to 30 cm^3/min, and a flow of 0.5 cm^3/min of fluorine was started. After 12 hr, the fluorine flow was increased to 0.75 cm^3/min and zone 1 was allowed to warm to equilibrium (−40°). After 8 hr, the fluorine flow was increased to 1.0 cm^3/min and the helium flow reduced to 20 cm^3/min. After 22 hr the fluorine flow was increased to 1.5 cm^3/min and zone 2 allowed to warm (Z_1 = −30, Z_2 = −50, Z_4 = 78°). After 30 hr, the fluorine flow was increased to 2.0 cm^3/min. After 24 hr the helium flow was reduced to 10 cm^3/min and zone 3 was allowed to warm. After 24 more hr, the helium flow was shut off and zone 4 was allowed to warm from −80 to 25° at a rate of 20°/day. The fluorine flow was terminated and the product which had collected in the −196° collection trap was hydrolyzed with 25 ml of 2.0 M KOH and fractionated on a vacuum line. The product which collected in the −95 and 78° traps was purified by gas chromatography (13% fluorosilicone QF-1-0065 on Chromosorb P).

Perfluoro-1,2-diethoxyethane is a clear, colorless, water-stable liquid (bp ~62°). The molecular weight determined by the ideal gas method was 370 (cf. 371 for $C_6F_{14}O_2$). The ^{19}F NMR consisted of a closely spaced quartet (J== 1.6 Hz) at +92.05 ppm and a pentet (J = 1.6 Hz) at +91.0 ppm of intensity 4:3, respectively. The infrared spectrum exhibited bands at 1245 (vs), 1220 (sh), 1155 (s), 1140 (s), 1102 (m), 837 (w), 788 (w), 733 (w), 703 (m), 690 (w), 648 (w), 550 (sh), 525 cm^{-1} (w). The mass spectrum contained strong peaks at *m/e* 185, C_3F_7O; 119, C_2F_5; 100, C_2F_4; 97, C_2F_3O; 69, CF_3; and 50, CF_2. The yield was 18%.

Anal. Calcd for $C_6F_{14}O_2$: C, 19.48; F, 71.88. Found: C, 19.53; F, 71.52.

Perfluoro-1,4-dioxane. In a typical experiment for the preparation of perfluoro-1,4-dioxane, approximately 3 ml (3.324 g, 0.0347 mol) of 1,4-dioxane was syringed into the evaporator (50°) of the fluorination reactor.[4] The design of the reactor has been previously reported[4] and is used as described. A flow of 160 cm^3/min of helium was used to evaporate the material into the gradient reactor. Zone 4 of the reactor was maintained at −78° and zone 1 at approximately 0 to −5°. After about 20 hr all four reactor zones were filled with Dry Ice. The flow of helium was reduced to 20 cm^3/min and a fluorine flow of 0.5 cm^3/min was initiated. After 12 hr, the fluorine flow was increased to 1.0 cm^3/min. Twelve hours later zone 1 started to warm. After equilibrium temperature was reached in zone 1 (~−40°) the fluorine flow was raised to 1.5 cm^3/min. Twelve hours later, zone 2 was allowed to warm (Z_1 = −20, Z_2 = −40° at equilibrium). When the equilibrium gradient temperatures stabilized (~12 hr), the helium flow was reduced to 12.5 cm^3/min and 12 hr later reduced to 7.5 cm^3/min. Twenty-four hours later the helium flow was reduced to 2.5 cm^3/min and zone 3 was allowed to warm. At equilibrium (Z_3 = −40, Z_2, −20, Z_1, −5°) the helium flow was stopped. A flow of 1.5 cm^3/min of fluorine was continued for 24 hr, then zones 1 and 2 were filled with ice and water. After 12 hr, zone 4 was allowed to warm and the glass collection trap initially maintained at −78° was cooled to −196° and a flow of 3.0 cm^3/min of helium was started. After 12 hr, the reactor was at ambient temperature and 6.9 g of volatiles had collected in the collection trap. The volatiles were condensed into a 500-ml bulb containing approximately 25 ml of frozen (−196°) 2.0 *M* KOH and sealed. The contents were allowed to warm over 1 hr to −78° and then to ambient overnight. The aqueous contents were frozen at −15° and the liquid and gas removed and fractionated. GLC assay of the contents of the −95 and −131° traps yielded 3.37 g (38.5%) of perfluoro-1,4-dioxane and 0.4 g (4%) of perfluoro-1,2-dimethoxyethane. The −196° trap contained 4.23 g (48%) of essentially pure perfluorodimethyl ether.

Perfluoro-1,4-dioxane is a gas at room temperature (bp 15.9°). The molecular weight determined by the ideal gas method was 232.7 (cf. 232.0 for $C_4F_8O_2$). The ^{19}F NMR consisted of a singlet at φ +90.78 ppm (relative to $CFCl_3$, external). The infrared spectrum exhibits bands at 1435 (w), 1369 (w), 1311 (sh), 1303 (s), 1232 (vs), 1163 (sh), 1149 (s), 1113 (s), 890 (m), 665 cm^{-1} (m). The mass spectrum shows no parent peak but shows a peak at *m/e* 213 corresponding to the molecular ion minus a fluorine $C_4F_7O_2$. Other strong peaks are *m/e* 119, C_2F_5; 100, C_2F_4; 69, CF_3; 50, CF_2; and 47, CFO.

Anal. Calcd for $C_4F_8O_2$: C, 20.706; F, 65.503. Found: C, 20.63; F, 65.67.

Perfluoro(ethyl acetate). In the preparation of perfluoro(ethyl acetate), ethyl acetate (1.74 g, 0.0198 mol) was syringed into the evaporator of the four-zone gradient reactor system. A flow of 150 cm^3/min helium evaporated the ethyl acetate into the gradient reactor which was maintained at −100°. After 6 hr, a flow of 0.5 cm^3/min of fluorine was initiated and the helium flow was reduced to 20 cm^3/min. After 16 hr, the fluorine flow was increased to 1.0 cm^3/min. After 8 hr, the fluorine was increased to 1.5 cm^3/min and the helium flow reduced to 10 cm^3/min while zone 1 was warmed to equilibrium (−70°). After 24 hr, the helium flow was reduced to 5 cm^3/min and zone 2 was warmed to equilibrium gradient (Z_1, −40, Z_2, −70°). After 12 hr, the helium flow was stopped. Twelve hours later, zone 3 was warmed to equilibrium gradient (Z_1, −30, Z_2, −50, Z_3, −70, Z_4, −100°). Twelve hours later the fluorine flow was increased to 2.0 cm^3/min. After 24 hr, zone 4 was warmed to −80° (Z_1, 10, Z_2, 0, Z_3 −45, Z_4, −80°). After an additional 24 hr, Z_4 was warmed to −45° and over the next 24 hr to ambient temperature (24°). The system was purged with helium and the product which had collected in the −196° trap was vacuum line fractionated through −63, −84, −95, −104, and −196° slush-cooled traps. Gas chromatographic separations (fluorosilicone QF1-0065, 13% in Chromosorb P) of the products collected in the −63 through −104° traps yielded the following products: $CF_3CO_2C_2F_5$, 0.23 g (5%); $CF_3CO_2CHFCF_3$, 0.85 g (20%); $CF_3CO_2CF_2CF_2H$, 0.05 g (1.2%); FCO_2CHFCF_3, 0.5 g (1.4%); the −196° trap also contained 2 g of a mixture of about equal parts CF_3CFO and CHF_2CFO.

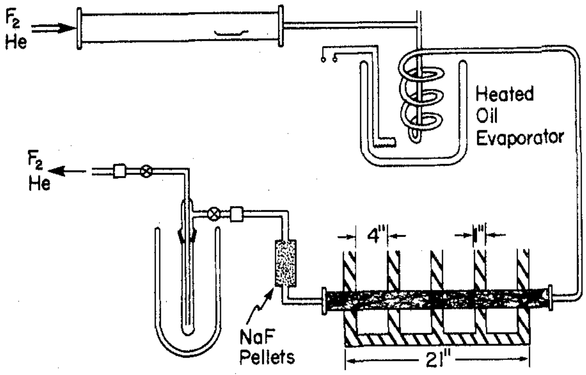
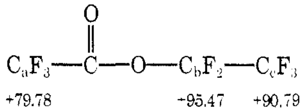


Figure 2. Multizone cryogenic reactor. Volatile liquids are vaporized into the first zone of the reactor from a nickel boat. Less volatile liquids are injected into the heated oil evaporator and vaporized into the reactor. After the reaction is complete, hydrogen fluoride is removed from products using a sodium fluoride pellet trap and products are collected in the liquid nitrogen trap. The excess fluorine is treated with 8–14 mesh Al_2O_3 to produce AlF_3 and release molecular oxygen.

Anal. Calcd for $C_4F_8O_2$: C, 20.706; F, 65.503. Found: C, 20.65; F, 65.48.

Perfluoro(ethyl acetate) is a moisture-sensitive gas (bp 21.4°) which was easily dissociated to 2 mol of trifluoroacetyl fluoride. The infrared spectrum of perfluoro(ethyl acetate) exhibits bands of 1848 (s) (νC=O), 1332 (m), 1245 (vs), 1213 (s), 1200 (s), 1173 (ms), 1109 (vs), 1089 (s), 855 (w), 832 (m), 677 (m), 618 cm^{-1} (sh). The ^{19}F NMR as a neat liquid relative to external $CFCl_3$ in carbon tetrachloride consisted of a sharp triplet (J = 0.4 Hz) at +79.78 ppm, a quartet (J = 2.4 Hz) at +95.45 ppm split into quartets (J = 0.4 Hz) and a triplet at +90.79 ppm (J = 2.4 Hz). The relative integrals were 3:2:3, respectively. The data are rationalized in Chart II, and compare well with those published by Shreeve and coworkers.[10] The major product isolated from the reaction of ethyl acetate and elemental fluorine was the trifluoroacetic acid ester of the unstable alcohol α-hydrotetrafluoroethyl alcohol. This fluoro alcohol ester is a moisture-sensitive liquid (bp 31.7°) which can be dissociated by a Lewis base into an equimolar mixture of trifluoroacetyl fluoride and trifluoroacetaldehyde. The product was identified by a molecular weight determination [214.2 (cf. 214 for $C_4F_7HO_2$)], infrared, and ^{19}F and ^1H nuclear magnetic resonance. The infrared spectrum exhibits bands at 2995 (, 1830 (s) (νC=O), 1420 (w), 1370 (w), 1331 (w),) 00 (s), 1248 (s), 1218 (vs), 1198 (vs), 1140 (s), 1105 (vs), 1062 (m), 920 (m), 733 (m), 698 (m), 628 (w), 580 (w), 550 cm^{-1} (w). The ^{19}F and ^1H nuclear magnetic resonance spectrum is summarized in Chart III. A major factor affecting yields in this reaction is presumed to be the rearrangement of perfluoro(ethyl acetate) to 2 mol of trifluoroacetyl fluoride catalyzed by the hydrogen fluoride by-product and perhaps by the fluoride ion from the sodium fluoride pellets used to absorb the hydrogen fluoride liberated in the reaction. In fact, no perfluoro(ethyl acetate) was obtained from the reaction unless the sodium fluoride charged hydrogen fluoride trap was cooled to at least −10°.

Chart II

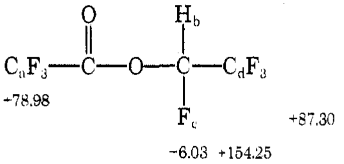


$$\underset{+79.78}{C_aF_3}-\overset{\overset{\displaystyle O}{\|}}{C}-O-\underset{-95.47}{C_bF_2}-\underset{+90.79}{C_cF_3}$$

$J_{ab} = 0.4$ Hz

$J_{bc} = 2.4$ Hz

Chart III



$$\underset{-78.98}{C_aF_3}-\overset{\overset{\displaystyle O}{\|}}{C}-O-\overset{\overset{\displaystyle H_b}{|}}{\underset{\underset{\displaystyle F_c}{|}}{C}}-C_dF_3$$

−6.03 +154.25 +87.30

$J_{ab} = \approx 0$

$J_{ac} = 0.5$

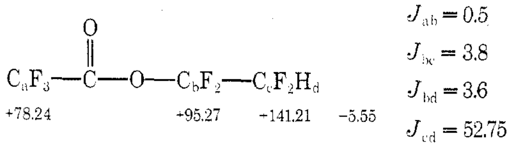
$J_{bc} = 50.53$

$J_{bd} = 3.05$

$J_{cd} = 5.87$

The β-hydrotetrafluoroethyl trifluoroacetate was characterized by an ideal gas method molecular weight determination (214.9, cf. 214.1) and its ^{19}F and ^{1}H NMR which is summarized in Chart IV.

Chart IV



$$C_aF_3{-}C({=}O){-}O{-}C_bF_2{-}C_cF_2H_d$$

The infrared spectrum contained bands at 3030 (w), 2995 (w), 1850 (m), 1833 (m), 1340 (w), 1302 (m), 1275 (w), 1250 (vs), 1206 (vs), 1150 (vs), 1132 (sh), 1101 (vs), 885 (w), 845 (w), 735 cm^{-1} (w).

The most important by-products, CF_3CFO and CHF_2CFO, are often obtained in yields as high as 40%; CF_4, OCF_2, and possibly $FCO_2C_2F_5$ are also produced in the reaction.

Perfluorodimethylmalonyl Difluoride. A 2.54-g (18.7 mmol) sample of dimethylmalonyl difluoride (mp 2°) was injected into the evaporator of the six-zone fluorination reactor. The first zone of the reactor was maintained at −8° and the dimethylmalonyl difluoride was evaporated at 20° into the first zone of the cryogenic reactor using a helium flow of 150 cm^3/min. After 24 hr the reactor was cooled to −78°, and a 0.5 cm^3/min flow of fluorine and a 20 cm^3/min flow of helium was initiated. This flow was maintained at this level for 3.5 days (95% total F_2 calculated for the reaction) at which time it was raised to 1.0 cm^3/min. On the first and second days the first and second zones were allowed to warm to equilibrium and on day 2.5 the helium was reduced to 10 cm^3/min. At day 4.0 the third zone was allowed to warm and the helium flow was reduced to 5 cm^3/min. On day 4.5 the helium was shut off. On day 5.5 the fluorine was increased to 1.5 cm^3/min and zone 4 was allowed to warm followed by zone 5 on day 6.5. On day 7.5 the temperature of zone 6 was raised to −50° by a temperature controller and zone 1 was heated to 20° by an immersion heater. On day 8.5 zone 6 was increased to 0° and one day later to 25°. The reactor was purged with helium for several hours, the glass trap was removed, and the contents were fractionated through −45, −78, −104, −130, and −196° traps. The major products, perfluorodimethylmalonyl difluoride (0.25 g, 5.5%) and difluoro-2-methylpropanoyl fluoride (0.51 g, 14%), and octafluoropropane were isolated from the −78 and 104° traps, respectively. The above materials were purified on a 0.375 in. × 10 m GLC column packed with fluorosilicone QF1-0065 (10% on 60–80 mesh Chromosorb P).

Perfluorodimethylmalonyl difluoride is a very volatile liquid above 11° (mp 10.5–11°, sealed tube). The molecular weight determined by the ideal gas method is 243.3 (cf. 244, $C_5F_8O_2$). The ^{19}F NMR consists of a heptet (J = 9.7 Hz) at ϕ −3.97 ppm and a triplet at ϕ +68.2 ppm with relative intensities 1:3. The mass spectrum exhibited a parent ion at m/e 244, a P − F at 225, a P − COF_2 at 178, a P − COF_3 at 159; 137, $C_4F_3O_2$; 69, CF_3; 47, CFO; the m/e 178, 69, and 47 peaks are the most intense.

Anal. Calcd: C, 24.25; F, 62.02. Found: C, 24.609; F, 62.279.

Perfluoropivaloyl Fluoride. For the preparation of perfluoropivaloyl fluoride, a 2-ml sample (1.961 g, 0.0188 mol) was injected into the evaporator of the fluorination reactor (a six-zone modification).[4] The reactor was maintained at −32° and the pivaloyl fluoride was evaporated at 25° into the first zone of the reactor using a helium flow of 150 cm^3/min. After 12 hr, the reactor was cooled to −78°; a 0.5 cm^3/min flow of fluorine and a 20 cm^3/min flow of helium were initiated. This flow was maintained at this level for 3 days (65% total F_2 calculated for reaction) during which time zones 1, 2, and 3 were warmed to their equilibrium temperature on successive days. On the fourth day, the helium was reduced to 10 cm^3/min and zone 4 was warmed. The fluorine flow was then increased to 1.0 cm^3/min for 3 more days (150% total F_2 calculated for reaction). At the end of the first day, the helium was reduced to 5 cm^3/min and then stopped completely on the second day. On the fourth day, the fluorine was increased to 1.5 cm^3/min and zone 6 was allowed to warm up by ≈25°/day until the reactor was warmed to 40° and maintained there by a thermostatic heater. The latter steps ensured that the crowded *tert*-butyl group would be completely fluorinated.

A crude yield of 4.4 g of material containing perfluoroisobutane, perfluoro-3,3-dimethyl-1-oxacyclobutane, perfluoropivaloyl fluoride, and monohydroctafluoropivaloyl fluoride was obtained. From this mixture, 2.6 g (52% ld) of perfluoropivaloyl fluoride was isolated. The monohydroacyl fluoride still makes up approximately 20% of the molar yield, the other two products making up most of the remaining material. The product is a very volatile solid (mp 38–38.5°, sealed tube) which sublimes readily at room temperature. The product has been characterized by ^{19}F NMR (a 95% solution in CCl_4) and consists of a dectet (J = 11.3 Hz) centered at −42.34 ppm and a doublet (J = 11.4 Hz) centered at +67.08 ppm relative to external $CFCl_3$–CCl_4. The relative integrals were 1:9.5. The mass spectrum contained a molecular ion at m/e 266, a P − F at 247, a P − COF_2 at 200, and other strong peaks at 181, C_4F_7; 178, C_4F_6; 159, C_4F_5O; 131, C_3F_5; 69, CF_3 (strongest peak); and 47, COF_2.

The infrared spectrum exhibited bands at 1880 (m, C–O), 1855 (sh), 1312 (sh), 1290 (vs), 1215 (m), 990 (s), 739 (w), 710 (w), 660 (w), 540 cm^{-1} (w).

Anal. Calcd for $C_5F_{10}O$: C, 22.574; F, 71.412. Found: C, 22.21; F, 71.47.

Results and Discussion

The direct fluorination of oxygen-containing hydrocarbons as a class of compounds represents a significant extention of the "LaMar" direct fluorination process to structures other than those containing only carbon and hydrogen. The term "oxygen containing" has been limited in this case to those compounds containing only carbon, hydrogen, oxygen, and fluorine. This group of compounds, a significant percentage of all functional hydrocarbons, includes acids, acyl fluorides, anhydrides, ketones, esters, ethers, and aldehydes. This paper is concerned primarily with the fluorination of ethers, esters, and acyl fluorides.

The carbon–oxygen single bond in hydrocarbons is of comparable strength with that of the carbon–carbon bond and therefore should resist fragmentation to an extent comparable to that found for the carbon–carbon bond. In general, this is found to be true; only in those cases where bonds are unstable in hydrogen fluoride or where unstable radicals can be formed, such as the acyl radical, are significant difficulties encountered. The first problem is due to the large amount of hydrogen fluoride liberated in the fluorination reactions; however, this problem can be reduced by keeping the system cold. The second problem is encountered in the acid derivatives which are converted to acyl fluorides via an intermediate acyl radical. This latter problem can be resolved by first converting the acid derivative to the acyl fluoride before fluorination of the alkyl group is attempted.

One of the significant problems in the electrolytic fluorination of ethers and especially ethylene glycol based diethers is the "β cleavage", the rupture of a carbon–carbon bond β to the ether linkage(s). The successful preparation of the "glyme" ethers, perfluoro-1,2-dimethoxyethane, perfluoro-1,2-diethoxyethane, and perfluorobis(2-methoxyethyl) ether, as well as the cyclic diether, perfluoro-1,4-dioxane, in good yields demonstrates that the problem of "β cleavage" is much less important in the system described herein. By contrast, the electrochemical fluorination of 1,4-dioxane, an example of "β cleavage", in which only perfluoro-1,2-dimethoxyethane was produced in 4% yield,[11] is the only previous synthesis reported for this compound.

The fluorination of hydrocarbon esters is one area in which direct fluorination yields the perfluorinated esters and other methods produce only the corresponding fluorocarbon acids. The direct fluorination of ethyl acetate represents the first successful fluorination of an ester. This is a difficult result to obtain even with direct fluorination and the primary reason for this difficulty is the instability of the ester linkage toward the hydrogen fluoride produced by the fluorination. However, the production of the perfluoroethyl and α-hydrotetrafluoroethyl trifluoroacetate esters in 5 and 20% yields, respectively, indicates that significant amounts of the ester products do survive under the conditions of the reaction. Recovery of the perfluorinated esters is also hampered by the very facile dissociation of the esters to two acyl fluoride functions in the presence of catalytic amounts of fluoride ion. In fact, the recovery of perfluorinated ester is not accomplished unless the sodium fluoride charged hydrogen fluoride trap is cooled to about −10°. This presumably reduces the activity of the sodium fluoride toward dissociation of the perfluoro ester. The reverse reaction is also known; fluoride ion functions as a catalyst in the production of a perfluorinated ester from 2 mol of acyl fluoride.[8] The α-hydro ester is also labile, but to a lesser extent. It can be produced by the reaction of trifluoroacetyl fluoride with trifluoroacetaldehyde in the presence of a Lewis base such as a tertiary amine.[12] The fact that the β-hydro ester is also produced in low yields indicates that it is the lability of the ester linkage in esters possessing the $-(CO)OCF_2-$ linkage which significantly reduces yields of the β-hydro (2%) and perfluoro esters (5%) relative to the α-hydrotetrafluoroethyl trifluoroacetate ester (20%). This is reasonable because the major difference between the α- and β-hydro esters is this lability, and statistically, one would expect them to be produced in comparable yields. It has also been noted that the purified β-hydro ester does not undergo spontaneous dehydrofluorination. The β-hydrotetrafluoroethyl trifluoroacetate ester can also be produced by fluoride ion catalyzed condensation of trifluoroacetyl fluoride and difluoroacetyl fluoride, although a mixture of products is obtained. On the other hand, condensation of difluoroacetyl fluoride yields the ester, $CHF_2(CO)OCF_2CHF_2$. Dehydrofluorination of the alcohol part could produce $CHF_2(CO)OCF{=}CF_2$, a potentially interesting monomer, and preliminary studies have been undertaken in this area.

The fluorination of highly branched hydrocarbons is an area in which direct fluorination has a distinct advantage. The direct fluorination of pivaloyl fluoride [$(CH_3)_3CCFO$], which yields perfluoropivaloyl fluoride in 52% yield, is a good example. By contrast, when potassium tetrafluorocobaltate(III) is the fluorinating agent pivaloyl fluoride is recovered unchanged.[13] This example shows that these are species for which direct fluorination is not only the best method but possibly the only suitable method. Previously, it had been proposed that highly branched hydrocarbons are more difficult to fluorinate.[14] The fluorination of highly branched structures by direct fluorination requires only that more reaction time at higher fluorine concentrations be used to replace the last few remaining hydrogens on these very crowded systems.

Perhaps one of the more interesting compounds prepared during the course of this work is perfluorodimethylmalonyl difluoride. This compound has many interesting possibilities. The most obvious is, of course, as a difunctional acid monomer in condensation reactions. Other interesting possibilities exist and are currently being investigated. The low yields of perfluorodimethylmalonyl difluoride are partially attributable to the instability of the hydrocarbon parent, dimethylmalonyl difluoride, which decomposes spontaneously at ambient temperature in a sealed tube (with about a 1-day half-life). The fluorocarbon appears to be stable.

The decomposition of the hydrocarbon produces a solid residue and gaseous products; however, decomposition may be arrested by storage at −15° or lower. The rather large relative yield of perfluoro-2-methylpropanoyl fluoride during the fluorination indicates that this system tends to undergo decarboylation at one point, possibly during evaporation of the hydrocarbon into the reactor which takes about 12 hr. If this is the case it should be possible to increase the yield dramatically by modification of the reactor system.

A discussion of the utility and important parameters for the cyrogenic reactor is presented in the Experimental Section. Although it is an idealization and simplification of the actual fluorination process, it is a helpful guide in designing a workable reaction program of flow rates and gradients. Maximization of parameters still requires trial and error, but knowledge of operation procedure for the system is approaching science rather than art.

Because the direct fluorination process described here is predominantly a radical process, complications can occur in systems which rearrange under these conditions. Protective groups, primarily steric, could be utilized to prevent extensive rearrangement or polymerization of sensitive functions. Radical recombination problems have been minimal despite the fact that the fluorination occurs in a condensed phase. Presumably this is because the radical sites occur in a scattered pattern among a group of molecules at high dilution of fluorine and since the bulk of the material remains solid, few radical sites can approach one another and combine. Also, as the system is fluorinated, steric and fluorine–fluorine repulsions become more important.

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Registry No.—Perfluoro-1,2-dimethoxyethane, 378-11-0; 1-hydrononafluoro-2,5-dioxahexane, 40891-98-3; perfluorobis(2-methoxyethyl) ether, 40891-99-4; perfluoro-1,2-diethoxyethane, 356-70-7; perfluoro-1,4-dioxane, 32981-22-9; perfluoro(ethyl acetate), 30950-31-9; α-hydrotetrafluoroethyl trifluoroacetate, 54214-47-0; β-hydrotetrafluorethyl trifluoroacetate, 54214-49-2; perfluoro-dimethylmalonyl difluoride, 42139-57-1; perfluoropivaloyl fluoride, 1813-18-9; fluorine, 7782-41-4; 1,2-dimethoxyethane, 110-71-4; bis(2-methoxyethyl) ether, 111-96-6; 1,2-diethoxyethane, 629-14-1; 1,4-dioxane, 123-91-9; ethyl acetate, 141-78-6; dimethylmalonyl difluoride, 870-75-7; pivaloryl fluoride, 430-71-7.

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