Radical Terpolymerization of 1,1,2-Trifluoro-2-pentafluorosulfanylethylene and Pentafluorosulfanylethylene in the Presence of Vinylidene Fluoride and Hexafluoropropylene by Iodine Transfer Polymerization

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ABSTRACT: Iodine transfer terpolymerization of two monomers bearing an SF_5 group, i.e., 1,1,2-trifluoro-2-pentafluorosulfanylethylene ($F_2C{=}CFSF_5$) and pentafluorosulfanylethylene ($H_2C{=}CHSF_5$), with 1,1-difluoroethylene (or vinylidene fluoride, VDF) and hexafluoropropylene (HFP) is presented. These pentafluorosulfanyl monomers present a peculiar reactivity. They do not homopolymerize by conventional radical polymerization, but they co- and terpolymerize with the above fluorinated olefins. The resulting fluorinated terpolymers were characterized by ^{19}F and ^1H NMR spectroscopies which enabled the assessment of the molar percentages of the three comonomers. Size exclusion chromatography and NMR characterizations were also used to assess the molecular weights, M_n, ranging between 260 and 8400 g/mol. Interestingly, both these pentafluorosulfanyl monomers exhibit different behaviors in that radical terpolymerization in the presence of $C_6F_{13}I$ as a degenerative chain transfer agent. Thus, CF_2CFSF_5 can be terpolymerized with VDF and HFP with a good control of molecular weight leading fluoropolymers bearing SF_5 groups with low polydispersity index (PDI). Unexpectedly, only two iodide functionalities of the terpolymers namely two end groups ($-CH_2CF_2I$ and $-CF_2CH_2I$) were observed and their proportions were influenced by the number of VDF units. Indeed, $-CH_2CF_2I$ functionality decreased when the number of VDFs per chain increased. In contrast to 1,1,2-trifluoro-2-pentafluorosulfanyl ethylene, $H_2C{=}CHSF_5$ could not be terpolymerized by ITP but led to $C_6F_{13}[(CH_2CF_2)(CH_2CH(SF_5)]_nI$ alternating cooligomers of low molecular weight in poor yields (5−20%). The formation of byproduct ($C_6F_{13}CH{=}CHSF_5$ monoadduct obtained by dehydrofluorination) was also observed, which corresponds to the elimination of HI from the 1:1 adduct. In the last part, the thermal properties are discussed. The presence of SF_5 group decreases the T_g of fluoropolymers whereas the thermal stabilities depended on the molecular weights.

Introduction

Fluoropolymers exhibit remarkable properties,[1−5] such as chemical inertness (to acids, bases, organic solvents), low dielectric constants and dissipation factors, hydrophobic and oleophobic properties, excellent weathering, and interesting surface properties. Hence, these high value-added-materials can find applications in many fields of high technology: aeronautics,[6] microelectronics,[7] optics,[8,9] textile finishing,[10,11] in the nuclear industry,[12] in paints and coatings[13] and military use.[14] Improvement of the properties of the fluoropolymers can be achieved from the copolymerization or the terpolymerization of monomers bearing functional group(s) born by the co- or termonomers. Among commercially available fluoroalkenes, vinylidene fluoride (VDF) is commonly used and regarded as an attractive monomer. It possesses a reactivity close to those of tetrafluoroethylene, trifluoroethylene and chlorotrifluoroethylene, but it is much less dangerous (it is not explosive and has a low toxicity) and is a precursor of thermoplastics or elastomers[4,5] endowed with interesting properties.

Pentafluorosulfanyl (SF_5) grouping polymers imparts original properties, such as high-performance lubricant and oil resistance properties, protective surface coatings, and insulating properties.[15−18] These interesting properties provide significant motivation to synthesize polymers bearing SF_5, e.g., polyfluoroalkyl acrylates,[19,20] polyfluoroalkylsiloxanes,[21] polyimides containing $SF_5(CF_2)_n-$ groups ($n = 0, 2$),[22] just like polystyrene bearing the $SF_5CF_2CF_2-$ group.[23] Thus, the use of monomers which possess an SF_5 group allowed the preparation of organic superconductors,[24] SF_5-organic metals/organic semiconductors,[25] ionic liquids,[26] and liquid crystals.[27] In a previous study,[28] the homopolymerization, copolymerization and terpolymerization of SF_5 containing-monomers with commercial fluoroalkenes was investigated by conventional radical polymerization. However, poor control of the molecular weights, the high polydispersity indexes (PDIs) and the presence of nonfunctional end groups to achieve functional or telechelic polymers was considered to limit the use (e.g., block copolymers or thermoplastic elastomers) and the applications of these copolymers. Therefore, to overcome these drawbacks, a major goal of this work became a controlled radical copolymerization of these monomers. Indeed, the peculiar reactivity of these fluorinated olefins allows the control of the radical polymerization by iodine transfer polymerization (ITP)[4,5,29] only. Actually, neither atom transfer radical polymerization (ATRP),[30] nor nitroxide mediated polymerization (NMP),[31] nor reversible addition fragmentation transfer (RAFT)[32] of fluorinated olefins has successfully been reported in the literature. ITP is a powerful technique which

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allows the synthesis of monofunctional and telechelic polymers terminated by iodine atom(s).[4,5,29] Such end groups can be modified to obtain polymers terminated by reactive groups. Furthermore, ITP allows the synthesis of different commercially available products, for example thermoplastic elastomers (TPE).[33−37]

The objectives of the present article concern the study of the radical terpolymerizations of VDF and hexafluoropropylene (HFP) with two different pentafluorosulfanyl monomers by iodine transfer terpolymerization in the presence of $C_6F_{13}I$ as a degenerative chain transfer agent. The influence of the structure of both the SF_5-monomers, i.e., $F_2C{=}CFSF_5$ and $H_2C{=}CHSF_5$, on the controlled character of the ITP was investigated, i.e., the correlation between targeted and experimental average degrees of polymerization (or average molecular weights) and the polydispersity indexes. Moreover, the behaviors between both these monomers according to the technique of polymerization (i.e., conventional and controlled radical polymerization) have also been compared. Indeed, different yields and compositions have been observed between both kinds of polymerization. In addition, the effect of the incorporation of SF_5-monomer during the polymerization of VDF onto the reversed additions has also been considered and compared to the results achieved from the ITP of VDF. Last, the thermal properties of the resulting fluorinated terpolymers vs the molecular weights have been investigated; these properties were not reported in our previous study.[28]

Experimental Section

Materials. Vinylidene fluoride (or 1,1-difluoroethylene, VDF), hexafluoropropylene (HFP) and 1,1,1,3,3-pentafluorobutane were kindly donated by Solvay S.A. (Tavaux, France, and Brussels, Belgium). 1-Iodoperfluorohexane ($C_6F_{13}I$, purity 95%) was generously supplied by Atofina (now Arkema, Pierre-Benite, France). It was treated with sodium thiosulfate and then distilled prior to use. *tert*-Butylperoxypivalate (TBPPI) (purity 75%) was a gift from Akzo, Chalons sur Marne, France, and was used as supplied. Acetonitrile, *N*,*N*′-dimethylformamide (DMF), tetrahydrofuran (THF), methanol, methylethylketone, and dimethylacetamide (DMAc) of analytical grade were purchased from Aldrich Chimie, 38299 Saint Quentin-Fallavier, France.

1,1,2-Trifluoro-2-pentafluorosulfanylethylene ($F_2C{=}CFSF_5$) was prepared as described in the literature[38] and the purity was checked by ^{19}F NMR and by FT-IR spectroscopies.

^{19}F NMR ($CDCl_3$, 298 K, 400 MHz, δ (ppm)): +69.7 (1F, SF_5), +59.0 (d, 4F, SF_5), −99.5 (m, $CF_2{=}$, 2F), −163.0 ppm (m, 1F, $={C}\underline{F}(SF_5)$).

FT-IR (cm^{-1}): 1782 (s, C=C), 1351 (s), 1246 (s), 1089 (m), 898 (vs), 862 (vs), 706 (m), 654 (m), 613 (s). The adsorptions at 898 and 862 cm^{-1} are assigned to S−F stretching while that at 613 cm^{-1} corresponds to one of the SF_5 group deformation modes.

The synthesis of pentafluorosulfanylethylene was as described in the literature[28,39] and checked by ^{19}F and ^{1}H NMR spectroscopies.

^{1}H NMR ($CDCl_3$, 298 K, 400 MHz, δ (ppm): 5.74 (m, 1H, $={CH}SF_5$), 6.01 (d, $J = 15$ Hz, 1H, $CH_2{=}$), 6.68 (m, 1H, $CH_2{=}$).

^{19}F NMR ($CDCl_3$, 298 K, 400 MHz, δ (ppm)): +81.4 (AB_4 system, J_{AB} 146 Hz, qi, 1F, SF_5), +59.7 (d, 4F, SF_5).

Note: Symbols s, d, t, qi, and m correspond to singlet, doublet, triplet, quintet, and multiplet, respectively. For IR, s, vs, and m stand for strong, very strong, and medium, respectively.

Analyses. The compositions and the structures of the terpolymers obtained by ITP were determined by ^{19}F and ^{1}H NMR spectroscopies. The NMR spectra were recorded on Bruker AC 200, AC 250, 400 (200, 250, and 400 MHz) instruments, using deuterated acetone and deuterated chloroform as the solvents and tetramethylsilane (TMS) (or $CFCl_3$) as the references for ^{1}H (or ^{19}F) nuclei. Coupling constants and chemical shifts are given in Hz and ppm, respectively. The experimental conditions for ^{1}H (or ^{19}F) NMR spectra were the following: flip angle 90° (or 30°), acquisition time 4.5 s (or 0.7 s), pulse delay 2 s (or 5 s), number of scans 16 (or 128), and a pulse width of 5 μs for ^{19}F NMR.

Gel permeation chromatography (GPC) or size exclusion chromatography (SEC) analyses were performed with a Spectra-Physics apparatus equipped with two PLgel 5 μm Mixed-C columns from Polymer Laboratories and a Spectra Physics SP8430 Refractive Index detector (the signals assigned to poly(VDF-*ter*-HFP-*ter*-SF_5 monomer) terpolymers gave negative values). Tetrahydrofuran (THF) was chosen as the eluent at $T = 30$ °C, with a flow rate of 0.8 mL min^{-1}. Monodispersed poly(styrene) standards were purchased from Polymer Laboratories. Aliquots were sampled from the reactional medium. Solvent was removed by evaporation, and after aliquots were diluted in THF up to a known concentration ca. 2 wt %, filtered through a 200 μm PTFE chromafil membrane, and finally analyzed by SEC.

Thermal Properties. The glass transition temperatures (T_gs) were determined by differential scanning calorimetry (DSC) using a Perkin-Elmer Pyris 1 apparatus calibrated with indium and *n*-decane. The samples (about 10 mg) were initially cooled to −105 °C for 10 min, then heated from −100 to 50 °C at a heating rate of 20 °C /min (a second recooling was done to −105 °C, and the same cycle was repeated three times). The values of T_gs reported herein correspond to the inflection point the heat capacity jump of the glass transition.

TGA analyses were performed with a Texas Instrument ATG 51−133 apparatus in air at the heating rate of 20 °C/min from room temperature up to 550 °C.

Reaction in Autoclave. Iodine transfer polymerizations of VDF, HFP and SF_5-monomers were performed in the presence of 1-iodoperfluorohexane as the degenerative chain transfer agent (CTA) and initiated by *tert*-butylperoxypivalate at 75 °C. A typical experiment is reported below with molar feed (VDF/HFP/ $F_2C{=}CFSF_5$): 75.2/ 16.5/ 8.3, $[C_6F_{13}I]_0/[VDF + HFP + SF5\ monomer]_0 = 0.056$, $[initiator]_0/[VDF + HFP + SF5\ monomer]_0 = 0.01$.

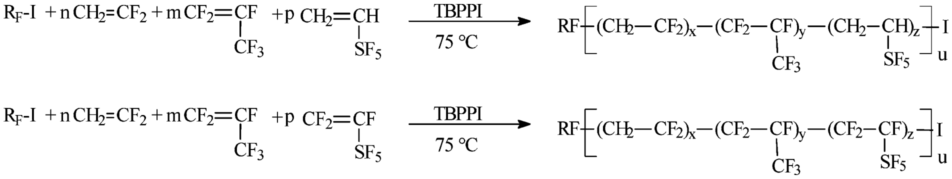
A 160 mL Hastelloy (HC-276) autoclave, equipped with inlet and outlet valves, a manometer, and a rupture disk, was degassed and pressurized with 30 bar of nitrogen to check for eventual leaks. Then, a 20 mmHg vacuum was imposed for 30 min. Under vacuum were transferred into the autoclave 0.320 g (1.38 mmol) of *tert*-butylperoxypivalate (TBPPI), 3.430 g (7.69 mmol) of 1-iodoperfluorohexane ($C_6F_{13}I$), 2.363 g (0.011 mol) of 1,1,2-trifluoro-2-pentafluorosulfanylethylene ($F_2C{=}CFSF_5$) and 35.0 g of 1,1,1,3,3-pentafluorobutane. Then, by double weighing, 3.4 g (0.02 mol) of HFP and 6.4 g (0.10 mol) of VDF were introduced in the mixture. Then, the autoclave was slowly heated to 75 °C. It was observed a low exotherm of ca. 5 °C and then a sharp drop of pressure from 10 bar to 1 bar. After 6 h of reaction, the autoclave was placed in an ice bath for about 60 min, and unreacted VDF, SF_5-monomers and HFP were progressively released. After the autoclave was opened, about 50.0 g of a brown liquid was obtained. The solvent and traces of monomers and CTA were removed by distillation at 60 °C under reduce pressure ($P = 20$ mmHg), to obtain a viscous and brown product. The sample was dissolved in acetone and precipitated from pentane to eliminate the traces of initiator and of CTA (yield = 80%). The terpolymer was characterized by ^{19}F and ^{1}H NMR spectroscopies, SEC, DSC and TGA analyses. The molecular weights were 1650 g/mol and 2100 g/mol, PDI = 1.36 with poly(styrene standard), assessed by ^{19}F NMR and by SEC analysis, respectively.

The same process was used for the radical terpolymerization involving pentafluorosulfanylethylene.

Results and Discusion

The radical terpolymerizations of fluorinated monomers bearing a $-SF_5$ group such as 1,1,2-trifluoro-2-pentafluorosulfanylethylene (i.e., $F_2C{=}CFSF_5$) and pentafluorosulfanylethylene (i.e., $H_2C{=}CHSF_5$) with 1,1-difluoroethylene (vinylidene fluoride, VDF) and hexafluoropropylene (HFP) were carried out in the presence of *tert*-butylperoxypivalate (TBPPI) as the initiator, with or without $C_6F_{13}I$ as the chain transfer agent

Scheme 1. Radical Terpolymerization of 1,1-Difluoroethylene (VDF), Hexafluoropropylene (HFP) and SF_5-Containing Monomers, i.e., 1,1,2-Trifluoro-2-pentafluorosulfanylethylene and Pentafluorosulfanylethylene in the Presence of 1-Iodoperfluorohexane ($C_6F_{13}I$) by Iodine Transfer Polymerization (ITP)[a]



[a] TBPPI stands for *tert*-butyl peroxypivalate.

(CTA), in 1,1,1,3,3-pentafluorobutane as the solvent at 75 °C for 14 h (Scheme 1).

During the course of the reaction, a drop of pressure was observed, which was assigned to the incorporation of both gaseous monomers into the terpolymers. After reaction, the solvent was removed by distillation, and the resulting terpolymers were purified by precipitation from cold pentane. After separation and drying, brown rubberlike polymers were obtained.

1. Mechanism of ITP. Iodine transfer polymerization (ITP) is a degenerative chain transfer polymerization (DT) requiring alkyl iodides.[4] ITP was developed in the late seventies by Tatemoto et al.[33−36] at the Daikin Company, and then was confirmed by other companies, such as du Pont de Nemours (now, Dupont Performance Elastomers)[40] and Ausimont[41−43] (now Solvay Solexis), and recently by Tosoh T-Tech Co.[44] The mechanism of iodine transfer polymerization (ITP) with alkyl iodide is shown in Scheme S1 in the Supporting Information.

The initiating radical, A^o, generated by thermal decomposition of a conventional initiator (such as *tert*-butylperoxypivalate, TBPPI) in step a, can be added onto M monomer (minor reaction) in step b or onto R−I (to lead to R^o, major reaction) in step b′, and the resulting radical propagates (step d). The exchange of iodine from the transfer agent, R−I, to the propagating radical, P_n^o, results in the formation of the polymeric alkyl iodide, P_n−I, and a new initiating radical, R^o (step c). Large differences in the stability of the reactants and products involved in step 4 could result in shifting the equilibrium overwhelmingly to the right or to the left. Therefore, the ideal case is when the structure of R closely looks like that of the propagating radical, resulting in a thermodynamically neutral transfer step. In step d, R^o, generated from the alkyl iodide, adds onto a monomer unit. The exchange process described in step 6 is thermodynamically neutral, because P_n and P_m propagating chains exhibit the same structure. As in any radical process, the termination occurs with alkyl iodides in ITP polymerization (step e). Minimizing the termination step remains essential to keep a good control of the polymerization (step f). Ideally, in ITP, to obtain polymer with a narrow molar mass-distribution the rate of exchange should be higher than that of the propagation. ITP allows one to control a great variety of hydrogenated monomers, such as acrylates,[45] styrenics,[45,46] methacrylates[47] (by reverse iodine transfer polymerization), and vinyl acetate,[48−50] and also fluorinated monomers,[4,5] such as VDF[29,51] or a mixture of fluoroolefins (VDF/HFP,[52,53] VDF/HFP/TFE,[54,55] VDF/MAF (where MAF represents α-trifluoromethacrylic acid[44]).... Finally, ITP allows the synthesis of well-defined architectures such as monofunctional and telechelic polymers,[4,5,37] PVDF-*b*-poly(styrene) diblock copolymer,[56] and PVDF-*g*-PS graft copolymer.[57]

2. Radical Terpolymerization of 1,1,2-Trifluoro-2-pentafluorosulfanylethylene ($F_2C{=}CFSF_5$) with Vinylidene Fluoride (VDF) and Hexafluoropropylene (HFP). 2.1. Characterizations of the Poly(VDF-*ter*-HFP-*ter*-SF_5M) Terpolymers by ^{1}H and ^{19}F NMR Spectroscopies. The microstructures of these resulting terpolymers were characterized by ^{1}H and ^{19}F NMR spectroscopies. Figure 1 represents the ^{19}F NMR of the terpolymers from an initial molar feed 74/18/8 of VDF/HFP/SF_5. This spectrum shows signals centered at −92.2 and at −92.4 ppm characteristic of the difluoromethylene groups of the head-to-tail VDF chaining (i.e., normal VDF addition) and a multiplet centered at −40.0 ppm assigned to CH_2CF_2I end group. Moreover, it is very interesting to note the absence of a series of signals centered at −94.9, −113.7, and −115.7 ppm assigned to $-CF_2-$ groups in $-(CH_2-CF_2)-(CF_2-CH_2)-(CH_2-C\underline{\mathbf{F_2}})-(CH_2-CF_2)$; $-(CH_2-C\underline{\mathbf{F_2}})-(CF_2-CH_2)-$; $-(CH_2-CF_2)-(C\underline{\mathbf{F_2}}-CH_2)-$ sequences, respectively, for the low molecular weight (Figure 1).[58] These sequences correspond to the reverse VDF addition (i.e., head-to-head addition).[59−62] Moreover, the presence of the $-SF_5$ monomer is confirmed by an AB_4 system ranging between +50 and +75 ppm. As expected, the difluoromethylene group of VDF adjacent to $-CF_2-CF(SF_5)-$ leads to a signal centered at −109.8 ppm, while those corresponding to CF_2 and CF are observed at −118.8 and −138.0 ppm, respectively.[28] Last, the signals centered at −183.5 and −119.0 ppm and from −71.2 to −76.0 ppm correspond to $C\underline{\mathbf{F}}$, $C\underline{\mathbf{F_2}}$ and $C\underline{\mathbf{F_3}}$ groups of hexafluoropropene (HFP).[53,63−65] The presence of the chain transfer agent was confirmed by the different signals centered at −82.0, −112.2, −122.5, −123.5, −124.0, and −127.0 ppm assigned to $C\underline{\mathbf{F_3}}$, $C\underline{\mathbf{F_2}}-CH_2$, $-C\underline{\mathbf{F_2}}-CF_2-CH_2$, $-C\underline{\mathbf{F_2}}-(CF_2)_2-CH_2$, $-C\underline{\mathbf{F_2}}-(CF_2)_3-CH_2$, and $CF_3-C\underline{\mathbf{F_2}}-$, respectively. The CTA conversion was evidenced by the absence of signal at −60.0 ppm assigned to the $-CF_2\mathit{CF}_2I$ end group. Thus, it is possible to assess the number of VDF, HFP and SF_5 monomeric units by the following equations:

$$\text{number of VDF units} = \mathrm{DP_n}^{\mathrm{VDF}} = [(\textstyle\int \mathrm{C}\mathbf{F_2}^{\text{at }-40.0\text{ ppm}} + \int \mathrm{C}\mathbf{F_2}^{\text{at }-92.0\text{ ppm}} + \int \mathrm{C}\mathbf{F_2}^{\text{at }-109.8\text{ ppm}} + \int \mathrm{C}\mathbf{F_2}^{\text{at }-113.7\text{ ppm}} + \int \mathrm{C}\mathbf{F_2}^{\text{at }-115.7\text{ ppm}})/2]/(\int \mathrm{C}\mathbf{F_3}^{\text{at }-82.0\text{ ppm}}/3) \quad (1)$$

$$\text{number of HFP units} = \mathrm{DP_n}^{\mathrm{HFP}} = (\textstyle\int \mathrm{C}\mathbf{F_3}^{\text{from }-71.0\text{ to }-76.0\text{ ppm}})/(\int \mathrm{C}\mathbf{F_3}^{\text{at }-82.0\text{ ppm}}) \quad (2)$$

$$\text{number of SF}_5\text{ monomers} = \mathrm{DP_n}^{\mathrm{SF5M}} = (\textstyle\int \mathrm{C}\mathbf{F}^{\text{at }-138\text{ ppm}})/(\int \mathrm{C}\mathbf{F_3}^{\text{at }-82.0\text{ ppm}}/3) \quad (3)$$

where $\int C\underline{\mathbf{F_x}}^{\text{at }-i\text{ ppm}}$ represents the integral of signal centered at −i ppm assigned to CF_x group.

The molecular weight, M_n, can also be calculated as follows: $M_n = \mathrm{DP_n}^{\mathrm{VDF}} \times 64 + \mathrm{DP_n}^{\mathrm{HFP}} \times 150 + \mathrm{DP_n}^{\mathrm{SF5}} \times 208 + 446$. The experimental results were close to the theoretical values assessed by equation $M_n = \mathrm{DP_{n,\,theoretical}}^{\mathrm{VDF}} \times 64 + \mathrm{DP_{n,\,theoretical}}^{\mathrm{HFP}} \times 150 + \mathrm{DP_{n,\,theoretical}}^{\mathrm{SF5}} \times 208 + 446$, with $\mathrm{DP_{n,\,theoretical}}^{\mathrm{M}} = \alpha \times [M]_0/[CTA]_0$, where α, M, $[CTA]_0$ and $[M]_0$ stand for the ratio of composition in M of terpolymer on the feed in M, the monomer (for example VDF, HFP or $F_2C{=}CFSF_5$), and the initial concentrations of chain transfer agent and of

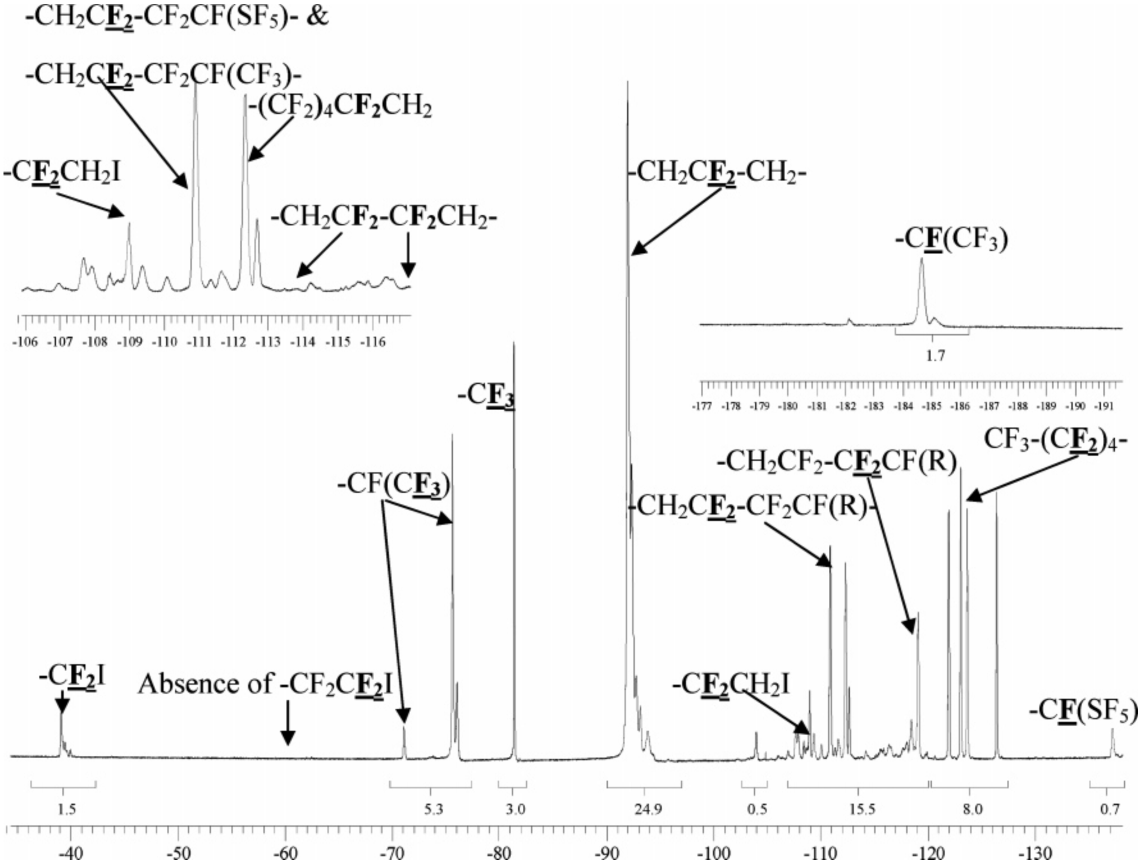


Figure 1. ^{19}F NMR spectrum of poly(VDF-*ter*-HFP-*ter*-CF_2CFSF_5) terpolymer obtained by ITP in the presence of $C_6F_{13}I$ at 75 °C (molar feed VDF/HFP/$CF_2CF(SF_5)$ ratio = 74.2/17.8/8.0, molar composition = 83.0/12.2/4.8, $M_{n,\ exp}$ (^{19}F NMR) = 1650 g/mol, $-CH_2CF_2I$ functionality = 0.75; run no. 2 in Table 1 (recorded in acetone-d_6, at 293 K, 400 MHz). Experimental conditions $[C_6F_{13}I]_0/[\text{VDF} + \text{HFP} + \text{SF5 monomer}]_0 = 0.05$, $[\text{initiator}]_0/[\text{VDF} + \text{HFP} + \text{SF5 monomer}]_0 = 0.01$ in 1,1,1,3,3-pentafluorobutane at 75 °C for 6 h.

monomer, respectively. Taking into account the fact that that HFP[4] and 1,1,2-trifluoro-2-pentafluorosulfanylethylene do not homopolymerize, their reactivity ratios are 0.

The compositions of monomeric $-CF_2-CF(SF_5)$, VDF, and HFP units in the terpolymers were assessed by ^{19}F NMR (e.g., Figure 1) from eqs 4, 5, and 6, respectively:

$$\begin{aligned}\%\ SF_5 = {}& \int C\mathbf{F}^{\text{at }-138\text{ ppm}}/[(\int C\mathbf{F_2}^{\text{at }-40.0\text{ ppm}} + \\ & \int C\mathbf{F_2}^{\text{at }-92.0\text{ ppm}} + \int C\mathbf{F_2}^{\text{from }-109.8\text{ to }-110.2\text{ ppm}} + \\ & \int C\mathbf{F_3}^{\text{at }-113.7} + \int C\mathbf{F_2}^{\text{at }-115.7})/2 + \\ & (\int C\mathbf{F_2}^{\text{from }-71.0\text{ to }-76.0\text{ ppm}})/3 + (\int C\mathbf{F}^{\text{at }-138\text{ ppm}})] \end{aligned} \tag{4}$$

$$\begin{aligned}\%\ \text{VDF} = {}& (\int C\mathbf{F_2}^{\text{at }-40.0\text{ ppm}} + \int C\mathbf{F_2}^{\text{at }-92.0\text{ ppm}} + \\ & \int C\mathbf{F_2}^{\text{from }-109.8\text{ to }-110.2\text{ ppm}} + \int C\mathbf{F_2}^{\text{at }-110.8\text{ ppm}} + \\ & \int C\mathbf{F_2}^{\text{at }-113.7} + \int C\mathbf{F_2}^{\text{at }-115.7})/2/[(\int C\mathbf{F_2}^{\text{at }-40.0\text{ ppm}} + \\ & \int C\mathbf{F_2}^{\text{at }-92.0\text{ ppm}} + \int C\mathbf{F_2}^{\text{from }-109.0} + \int C\mathbf{F_2}^{\text{at }-113.7} + \\ & \int C\mathbf{F_2}^{\text{at }-115.7})/2 + (\int C\mathbf{F_3}^{\text{from }-71.2\text{ to }-76.04\text{ ppm}})/3 + \\ & (\int C\mathbf{F}^{\text{ at }-138\text{ ppm}})] \end{aligned} \tag{5}$$

$$\begin{aligned}\%\ \text{HFP} = {}& \\ & [(\int C\mathbf{F_3}^{\text{from }-71.2\text{ to }76.04\text{ ppm}})/3]/[(\int C\mathbf{F_2}^{\text{at }-40.0\text{ ppm}} + \\ & \int C\mathbf{F_2}^{\text{at }-92.0\text{ ppm}} + \int C\mathbf{F_2}^{\text{from }-109.8\text{ to }-110.2\text{ ppm}} + \\ & \int C\mathbf{F_2}^{\text{at }-110.8\text{ ppm}} + \int C\mathbf{F_2}^{\text{at }-113.7} + \int C\mathbf{F_2}^{\text{at }-115.7})/2 + \\ & (\int C\mathbf{F_3}^{\text{from }-71.2\text{ to }-76.0\text{ ppm}})/3 + (\int C\mathbf{F}^{\text{at }-138\text{ ppm}})] \end{aligned} \tag{6}$$

with $C\underline{\mathbf{F}}^{\text{at }-138\text{ ppm}}$, $(\int C\underline{\mathbf{F_2}}^{\text{at }-40.0\text{ ppm}} + \int C\underline{\mathbf{F_2}}^{\text{at }-92.0\text{ ppm}} + \int C\underline{\mathbf{F_2}}^{\text{from }-108.8\text{ to }-115.7\text{ ppm}})$, and $\int C\underline{\mathbf{F_3}}^{\text{from }-71.2\text{ to }-76.0\text{ ppm}}$ correspond to monomer-bearing SF_5 group, VDF, and HFP units.

Interestingly, in contrast to a previous study,[28] the absence (or the weak integral) of signals assigned to $CH_2CF_2-CF_2CH_2-$ reversed VDF adducts can also evidence the controlled behavior of that terpolymerization.

The compositions of the terpolymers are given in Table 1. Whatever the concentration of the chain transfer agent, they were close (runs 2−4) to the compositions obtained by conventional radical polymerization (run 1) under the same experimental conditions. Moreover, the final molar percentages of VDF are higher than those in the feed and are in good agreement with those assessed from the conventional radical polymerization observed in our previous work.[28]

Finally, it is noted the absence (or not detectable by ^{19}F NMR) of signal assigned to the end group of direct initiation by radicals generated from the decomposition of the initiator, such as $(CH_3)_3C-CH_2C\underline{\mathbf{F_2}}-CH_2CF_2-$, $CH_3-CH_2C\underline{\mathbf{F_2}}-CH_2CF_2-$, $CH_3C\underline{\mathbf{F_2}}-CF_2CH_2-CF_2-$ and $(CH_3)_3C-C\underline{\mathbf{F_2}}CH_2-CF_2-$, which appears at −92.2, −95.7, −107.5, and −112.3 ppm.[28] The absence of the direct initiation is attributed to the high transfer constant of $C_6F_{13}I$.[51]

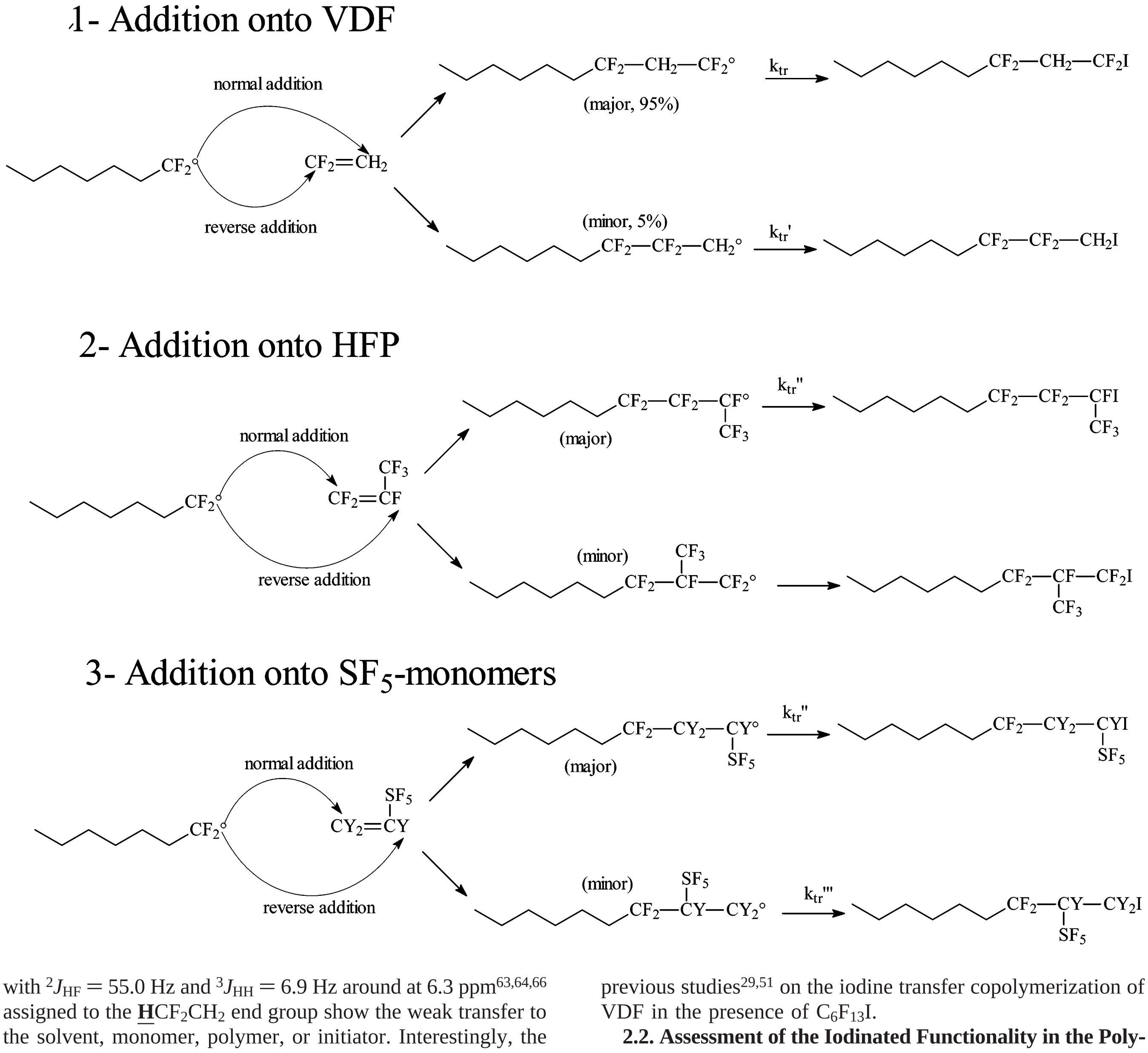
The ^{1}H NMR spectra (Figures S5 and S6 in the Supporting Information) of poly(VDF-*ter*-HFP-*ter*-$CF_2CF(SF_5)$) terpolymers for two concentrations of chain transfer agent (CTA) (Table 1) shows different signals centered at 3.3, 3.8, and 4.0 ppm attributed to methylene groups of VDF, $-C\underline{\mathbf{H_2}}CF_2I$, and $-C\underline{\mathbf{H_2}}$-I, respectively. The quasi-absence of the triplet of triplets

Table 1. Assessment of the Compositions of Comonomers in the Poly(VDF-*ter*-HFP-*ter*-SF_5M) Terpolymers, from Eqs 1−6, vs Different Radical Terpolymerizations of Vinylidene Fluoride (VDF), Hexafluoropropylene (HFP), and SF_5 Monomers in the Presence of $C_6F_{13}I$ as the Chain Transfer Agent at 75 °C for 6 h

		feed (mol %)			composition (mol %)			M_n				
runs	R_0	VDF	HFP	SF_5	VDF	HFP	SF_5	theoretical (g/mol)	SEC[d] (g/mol)	PDI[b]	M_n ^{19}F NMR (g/mol)	yield (%)
1	*a*	73.1	18.3	8.6	78.3	16.4	5.5		10 000	2.40		80
2[b]	0.05	74.2	17.8	8.0	83.3	12.2	4.8	2060	2100	1.36	1650	85
3[b]	0.02	74.5	18.5	7.0	80.5	16.1	3.4	5160	4550	1.38	4050	90
4[b]	0.01	75.6	17.2	7.2	80.2	15.0	4.8	10 320	10 400	1.48	8400	90
5[c]	0.05	74.0	18.0	8.0	61.8	2.0	36.2	2000	600	1.32	260	12
6[c]	0.01	75.0	17.5	7.5	58.9	1.1	40.0	5100	600	1.35	300	5

[a] Without any chain transfer agent. [b] With $F_2C{=}CFSF_5$ as the comonomer. [c] With $H_2C{=}CHSF_5$ as the comonomer. [d] Assessed from SEC using THF as the solvent with polystyrene standards.

Scheme 2. Different Reactions of Transfer in the Radical Terpolymerization of Vinylidene Fluoride (VDF), Hexafluopropene (HFP) and SF_5-Monomers (Y Corresponds to H or F)



with $^2J_{HF} = 55.0$ Hz and $^3J_{HH} = 6.9$ Hz around at 6.3 ppm[63,64,66] assigned to the $\underline{\mathbf{H}}CF_2CH_2$ end group show the weak transfer to the solvent, monomer, polymer, or initiator. Interestingly, the peak centered at 2.5 ppm of negligible intensity shows the *quasi*-absence of tail-to-tail addition of VDF ($-CF_2-C\underline{H_2}-C\underline{H_2}-CF_2-$) for both low and high molecular weights. This may be an evidence of the controlled radical copolymerization showing that each VDF unit is incorporated in a regioselective way in the poly(VDF-*ter*-HFP-*ter*-$CF_2CF(SF_5)$) terpolymers. This also indicates the high transfer constant of $C_6F_{13}I$ and confirms previous studies[29,51] on the iodine transfer copolymerization of VDF in the presence of $C_6F_{13}I$.

2.2. Assessment of the Iodinated Functionality in the Poly(VDF—HFP—SF_5M) Terpolymers. In the course of the radical terpolymerization of VDF, HFP and SF_5 monomers in the presence of $C_6F_{13}I$, it is possible to obtain six chain ends, i.e., $-CH_2CF_2I$, $-CF_2CH_2I$, $-CF(CF_3)CF_2I$, $-CF_2CF(CF_3)I$, $-CF(SF_5)CF_2I$, and $-CF_2CF(SF_5)I$ (Scheme 2). The amount of each species can be determined by ^{19}F NMR. Indeed, these different structures should lead to different signals as sum-

Table 2. Chemical Shifts of Different Compounds Bearing a C−I Bond According to the Substituents

monomers	compounds	δ (^{19}F NMR) (ppm)	δ (^{1}H NMR) (ppm)	ref
TFE, tetrafluoroethylene	$-CF_2-C\mathbf{F}(F)I$	−60.0		67, 71
TrFE, trifluoroethylene	$-CF_2-C\underline{\mathbf{F}}(H)I$	−167.7	7.2	71, 72
	$-CF(H)-C\underline{\mathbf{F_2}}I$	−54.5	5.1	
VDF, 1,1-difluoroethylene	$-CH_2-C\underline{\mathbf{F}}(F)I$	−40.0 (−39)[a]	3.6	51, 59
	$-C\underline{\mathbf{F_2}}-CH_2I$	−109.0	3.8	
CTFE, chlorotrifluoroethylene	$-CF(Cl)-C\underline{\mathbf{F_2}}I$	−55.0		68
	$-CF_2-C\mathbf{F}(Cl)I$	−72.4		
HFP, hexafluoropropene	$-CF_2-C\underline{\mathbf{F}}(CF_3)I$	−145.0		70
	$-CF(CF_3)-C\underline{\mathbf{F_2}}I$	−60.0		
PMVE, perfluoromethylvinylether	$-CF(OCF_3)-C\underline{\mathbf{F_2}}I$	−60.0	-	73
	$-CF_2-C\underline{\mathbf{F}}(OCF_3)I$	−73.0	-	
$F_2C{=}CFSF_5$, 1,1,2-trifluoro-2-pentafluorosulfanylethylene	$-CF(SF_5)-C\mathbf{F_2}I$	−63.8	-	21, 71
	$-C\underline{F_2}-C\underline{\mathbf{F}}(SF_5)\ I$	−58.8	-	
$H_2C{=}CHSF_5$, pentafluorosulfanylethylene	$-CH(SF_5)-C\mathbf{H_2}I$	-	3.6	21
	$-C\underline{\mathbf{H}}(SF_5)I$	-	4.4	

marized in Table 2[61,67−73]. The $-CH_2CF_2I$ and $-CF_2CH_2I$ chain ends correspond to the normal and the reverse addition of C−I bond onto VDF (Scheme S2 in the Supporting Information). Their corresponding signals appear at −40.0 and −109.0 ppm. However, it is noted the absence of signals centered at −60.0 and −145.0 ppm, which correspond to $-CF(CF_3)CF_2I$ and $-CF_2CF(CF_3)I$ chain ends comprising reverse and normal addition of radical onto HFP,[70] respectively (Table 2). Finally, it is also interesting to note the absence of the SF_5-monomer chain end. The great reactivity of these iodides explains the absence of such signals. Thus, when these species are formed during the reaction, they rapidly transfer. Thus, the polymeric chains terminated by $-CF_2CF(CF_3)I$, $-CF(CF_3)CF_2I$, $-CF(SF_5)CF_2I$, and $-CF_2CF(SF_5)I$, are quickly consumed, while the other species (i.e., $-CH_2CF_2I$ and $-CF_2CH_2I$), which present a weaker reactivity, are more slowly consumed.

$-CF_2CH_2I$ and $-CH_2CF_2I$ functionalities were assessed by the following equations.

$$\text{functionality in } -CH_2-C\mathbf{F_2}I = \left(\int -CH_2C\mathbf{F_2}I^{-40.0\text{ ppm}}/2\right)/\left(\int -C\mathbf{F_3}^{-82.0\text{ ppm}}/3\right) \quad (7)$$

$$\text{functionality in } -CF_2-C\mathbf{H_2}I = \left(\int -CF_2C\mathbf{H_2}I^{-109.0\text{ ppm}}/2\right)/\left(\int -C\mathbf{F_3}^{-82.0\text{ ppm}}/3\right) \quad (8)$$

The sum of $-CH_2-CF_2I$ and $-CF_2-CH_2I$ functionalities was 1, hence confirming the absence of terpolymers terminated by $-CF(SF_5)C\underline{\mathbf{F_2}}I$, $-CF_2C\underline{\mathbf{F}}(SF_5)I$, $-CF_2C\underline{\mathbf{F}}(CF_3)I$, and $-CF(CF_3)C\underline{\mathbf{F_2}}I$.

Further, according to the CTA concentration in the medium, the functionalities in $-CH_2CF_2I$ and $-CF_2CH_2I$ are different. Indeed, a decrease of CTA concentration (and hence an increase of the molecular weight) induces a decrease $-CH_2-C\mathbf{F_2I}$ functionality (from 0.7 to 0.3). The low reactivity of $-CH_2I$ explains its accumulation in the reactional medium (Table 3). This observation is in agreement with the results obtained for the ITP of VDF in the presence of CTA.[29,51] Indeed, VDF is an unsymmetrical monomer and the produced macroradical generated in the propagation step may add onto CF_2 or CH_2 sites (Scheme 2 in Supporting Information).[51] As a matter of fact, it is known that PVDF contain microstructures defects linked to the presence of reversed VDF addition since tail-to-tail, or head-to-head chainings have been observed (Figures S1−3 in the Supporting Information).[29,51] Nevertheless, the $-CF_2I$ proportions in the terpolymers are higher than those obtained in the case of the PVDF homopolymer synthesized by ITP in the presence of VDF and of $C_6F_{13}I$, only (Figure 2). In conclusion, the addition of comonomer in the polymerization decreases the reverse addition and improves the control of ITP.

Table 3. Results of the Functionality Obtained by Iodine Transfer Terpolymerization of VDF, HFP and SF_5-monomers

		feed (mol %)			functionality			
runs	R_0	VDF	HFP	SF_5	$-CH_2$-CF_2I	$-CF_2$-CH_2I	$-CY(SF_5)$-CY_2I	$-CY_2$-$CY(SF_5)I$
1[a]		73.1	18.3	8.6				
2[b]	0.05	74.2	17.8	8.0	0.70	0.30	0	0
3[b]	0.02	74.5	18.5	7.0	0.20	0.80	0	0
4[b]	0.01	75.6	17.2	7.2	0.05	0.95	0	0
5[c]	0.05	74.0	18.0	8.0	0.30	0	0	0.70
6[c]	0.01	75.0	17.5	7.5	0.25	0	0	0.65

[a] Without any chain transfer agent. [b] With $F_2C{=}CFSF_5$ as the comonomer. [c] With $H_2C{=}CHSF_5$ as the comonomer.

2.3. Influence of the CTA Concentration onto the Molecular Weights of Poly(VDF-*ter*-HFP-*ter*-SF5M) Terpolymers.

Different reactions were carried out with the same VDF/HFP/CF_2CFSF_5 feed and in the presence of different $[CTA]_0/[VDF + HFP + CF_2CF(SF_5)]_0$ molar ratios, R_0, ranging from 0.005 to 0.05. The molecular weights were assessed by SEC analysis (with a calibration made of polystyrene standards) and by ^{19}F NMR. As expected, these samples are soluble in THF and their molecular weights can be characterized by SEC. Figure 3 exhibits different SEC traces of poly(VDF-*ter*-HFP-*ter*-CF_2-$CFSF_5$) terpolymers vs different CTA concentrations.

Interestingly, according to the R_0 ratio, the experimental molecular weights are different (depending on the initial CTA concentration) and close to the theoretical values (Figure 3). The polydispersity index (PDI) values are relatively low, which indicates that the radical polymerization is controlled to some extent. Indeed, runs 2−4 led to PDI values of 1.36, 1.38 and 1.48, respectively, in contrast to run 1 (without any CTA) that yielded a terpolymer with PDI = 2.40. Thus, the $C_6F_{13}I$ allows control of the molecular weight in the presence of 1,1,2-trifluoro-2-pentafluorosulfanylethylene ($CF_2{=}CF(SF_5)$) with a suitable PDI value.

2.4. Evolution of the Molecular Weights and PDI vs Monomer Conversion.

Finally, the evolution of the molecular weights and of the polydispersity indexes (PDIs) vs the monomer conversion has been supplied for ITP (Figure 4). The molecular weights, as determined by SEC and by ^{19}F NMR, are in good agreement with the theoretical values. Interestingly, these molecular weights increase linearly vs the monomer conversion. PDI values are close to 1.3−1.5. The slight increase of PDI values during the polymerization can be attributed to the accumulation of the $-CH_2I$ end group of the terpolymers due to the reverse addition of VDF and they are not able to reinitiate another chain (Figure 4B, see Scheme S2 in the Supporting Information). Indeed, such terpolymers exhibit low transfer constant values (lower than 1) in contrast to those of the terpolymers containing a $-CF_2I$ end group, which possess transfer constants higher than 7,[29,51] which thus explains the increase of these PDI values. Nevertheless, it can be conclude that such a terpolymerization shows a controlled/“*pseudo*living” behavior.

3. Radical Terpolymerization of VDF with HFP and $H_2C{=}CHSF_5$.

The same above reaction was carried out in the presence of $CH_2{=}CHSF_5$ monomer instead of $F_2C{=}CFSF_5$; i.e., a similar initial molar feed of 74/17/9 was chosen for VDF/HFP/SF_5. During the course of the reaction, a slight drop of pressure (from

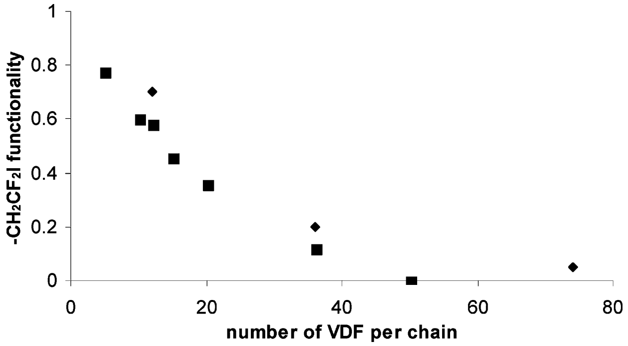


Figure 2. Evolution of $-CH_2CF_2I$ functionality vs the number of VDF units per chain for poly(VDF-*ter*-HFP-*ter*-CF_2CFSF_5) terpolymer (◆) and for PVDF−I homopolymer (■) obtained by iodine transfer polymerization of VDF in the presence of $C_6F_{13}I$ as the degenerative chain transfer agent, in the same following experimental conditions: $[\text{initiator}]_0/[\text{VDF} + \text{HFP} + \text{SF5 monomer}]_0$ or $[\text{initiator}]_0/[\text{VDF}]_0 = 0.01$ in 1,1,1,3,3-pentafluorobutane at 75 °C for 6 h.

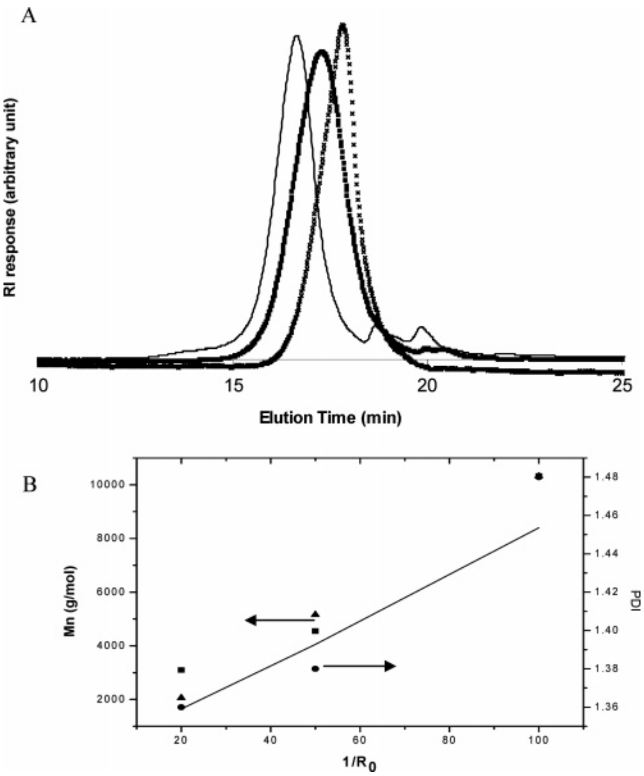


Figure 3. (A) SEC chromatograms of poly(VDF-*ter*-HFP-*ter*-SF_5-monomers) terpolymers obtained by iodine transfer polymerization of vinylidene fluoride, hexafluoropropylene and SF_5-monomers (×) run 2 ($R_0 = 0.05$); (■) run 3 ($R_0 = 0.01$); (full line) run 4 ($R_0 = 0.005$), respectively. (B) Evolution of molecular weight (M_n, ■ and ▲ assessed by SEC and ^{19}F NMR, and theoretical value (full line), respectively) and polydispersity index (PDI, ●) vs $1/R_o$ ($R_o = [C_6F_{13}I]/[M]$ where [M] represents the monomer concentrations). Experimental conditions $[\text{initiator}]_0/[\text{VDF} + \text{HFP} + \text{SF5 monomer}]_0 = 0.01$ in the 1,1,1,3,3-pentafluorobutane at 75 °C for 6 h. The straight line is the theorical curve.

15 to 12 bar) was observed, which was assigned to the incorporation of the gaseous monomers into the terpolymers. After reaction and purification, the resulting terpolymer obtained in poor yield (<20%) was characterized by ^{19}F and ^{1}H NMR spectroscopy and by SEC.

Figure 5 displays the ^{19}F NMR spectrum of poly(VDF-*ter*-SF_5-*ter*-HFP) terpolymer. First, the absence of $-CF_2C\underline{\mathbf{F_2}}I$ signal centered at −60.0 ppm confirms the quantitative consumption of chain transfer agent (CTA). Also observed is the absence of the signals assigned to HFP units (absences of signals at −71, −75, −120 and −186 ppm), in the terpolymer and poor incorporation of VDF (the signal centered at −92.0 ppm has a small integral). Conversely to the previous monomer, the presence of the multiplet centered at −112.0 ppm was assigned to $-CF_2-C\underline{\mathbf{F_2}}\text{-}CH_2-CH(SF_5)-$. However, the incorporation of SF_5 monomer has been confirmed by the multiplet ranging from +50 to +80 ppm characteristic of the SF_5 group. It is interesting to observe that the functionality in $-CH_2CF_2I$ (signal centered at −40.0 ppm) worth 0.3, whereas the absence of $\text{-}C\underline{\mathbf{F_2}}CH_2I$ (centered at −109.0 ppm) confirms the absence of reverse addition of VDF during the polymerization. Thus, the terpolymers are terminated mainly by $-CH_2C\underline{\mathbf{H}}(SF_5)I$ though there are traces of $-C\underline{\mathbf{H}}{=}CHSF_5$.

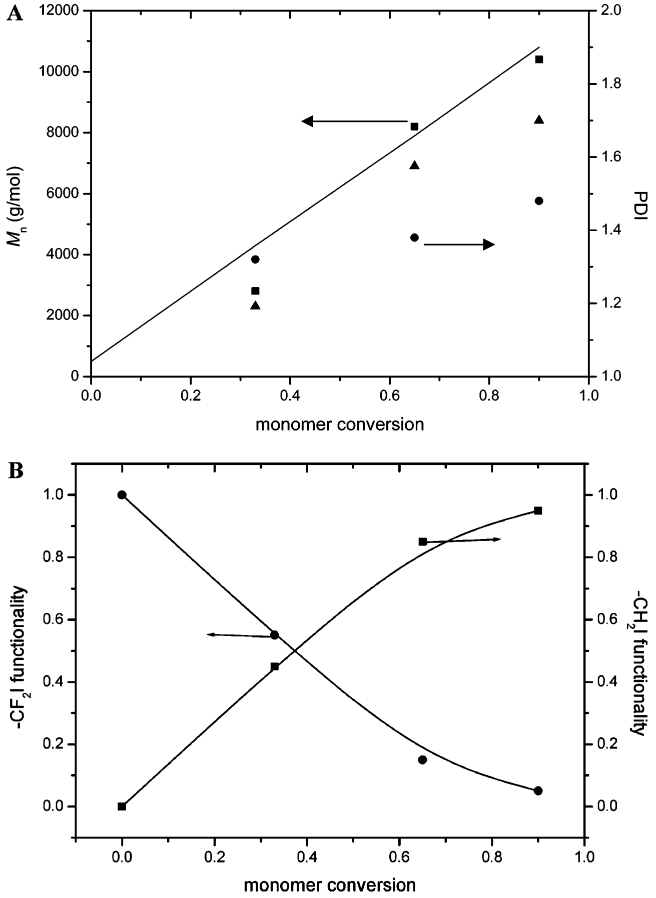


Figure 4. (A) Evolution of molecular weights (▲) assessed by ^{19}F NMR and (■) SEC, with the full line corresponding to theoretical value, and (●) PDI vs overall monomer conversion. (B) evolution of (●) $-CF_2I$ and (■) $-CH_2I$ functionality vs monomer conversion.

^{1}H NMR spectrum (Figure S7 in the Supporting Information) confirms this characterization by the presence of signals at 3.8 and 4.4 ppm assigned to $-CF_2CF_2-C\underline{\mathbf{H_2}}CH(SF_5)I$ and $-CH_2C\underline{\mathbf{H}}\text{-}(SF_5)I$, respectively. Moreover, the low incorporation of VDF is confirmed by the low intensity of signal centered at 2.8−3.0 ppm. In contrast to the above case, it is noted the presence of $-CF_2H$ signal (6.3−6.5 ppm) arising from to the transfer reaction to the polymer, the monomer or the solvent. If we compare this result with those obtained when $CF_2{=}CFSF_5$ was involved in the terpolymerization, $CH_2{=}CHSF_5$ monomer exhibits a higher transfer. Moreover, the presence of signal at 5.8−6.0 ppm can be attributed at the formation of $-C\underline{\mathbf{H}}{=}CH\text{-}(SF_5)$ species obtained by dehydroiodination of $-C\underline{H_2}-CH\text{-}(SF_5)-I$. Indeed, it can be assumed that the highly electrone-

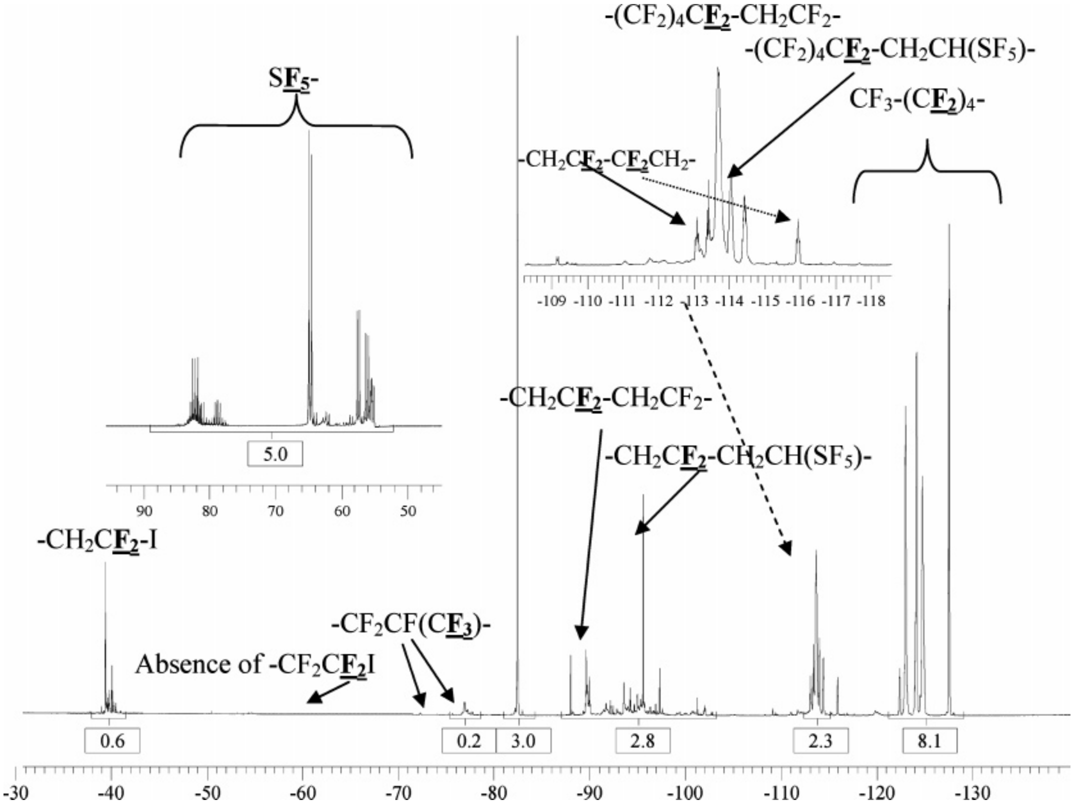


Figure 5. ^{19}F NMR spectrum of poly(VDF-*ter*-HFP-*ter*-CH_2CHSF_5) terpolymer obtained by iodine transfer polymerization in the presence of $C_6F_{13}I$ at 75 °C (molar feed VDF/HFP/$CH_2CH(SF_5)$ = 74.0/18.0/8.0), $-CH_2CF_2I$ functionality = 0.30. (Recorded in acetone-d_6, at 293 K, 400 MHz). Experimental conditions: $[C_6F_{13}I]_0/[VDF + HFP + SF5\ monomer]_0 = 0.05$, $[initiator]_0/[VDF + HFP + SF5\ monomer]_0 = 0.01$ in 1,1,1,3,3-pentafluorobutane at 75 °C for 6 h run no. 5 in Table 1.

gative SF_5 induces the easiness of iodine living group.

In conclusion of this NMR study, we observe for the terpolymerization of VDF, HFP and $H_2C{=}CHSF_5$ the formation of an alternate structure, i.e., C_6F_{13}-$[CH_2CF_2-CH_2CH(SF_5)]_n-I$, of low molecular weight. This assumption was confirmed by the absence of signal centered at −92.0 ppm (assigned to the normal VDF addition $-CH_2C\underline{\mathbf{F_2}}$-$CH_2C\underline{\mathbf{F_2}}-$) attributed to VDF and the absence of ($-C\underline{\mathbf{H_2}}CF_2-C\underline{\mathbf{H_2}}CF_2-$) in ^{1}H NMR is in good agreement with this assumption.

SEC analysis shows that the terpolymer obtained exhibits a low molecular weight and low polydispersity index (M_n = 600 g/mol and PDI = 1.2 (Table 1)). The experimental and targeted molecular weights are not in agreement ($M_{n,targeted}$ = 2000 and 5000 g/mol). The same result was obtained when using different CTA concentrations. The major obtained product corresponds to the monoaddition of $C_6F_{13}I$ onto $CH_2{=}CHSF_5$ (leading to $C_6F_{13}CH_2CH(SF_5)I$). The C−I bond of this product (i.e., C_6F_{13}-$CH_2CH(SF_5)I$) appears to be very stable and does not react (and hence does not lead to any transfer).

In conclusion, pentafluorosulfanylethylene cannot be terpolymerized in the presence of VDF and HFP by iodine transfer polymerization in suitable yields as for $F_2C{=}CFSF_5$. Indeed, after radical addition of $-CF_2I$ onto $CH_2CH(SF_5)$, the produced species $-CF_2-CH_2CH(SF_5)-I$ exhibits a low transfer constant and cannot be used as a further macrotransfer agent.

4. Thermal Properties. The thermal properties of poly(VDF-*ter*-HFP-*ter*-CF_2CFSF_5) and poly(VDF-*ter*-HFP-*ter*-CH_2CHSF_5) terpolymers were assessed by differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA).

The TGA thermograms (Figure 6) show that even for low molecular-weight terpolymers, the poly(VDF-*ter*-HFP-*ter*-CF_2-$CF(SF_5)$) terpolymers exhibit good thermal stability since their decomposition started from 250 to 300 °C. If one compares these results with those obtained from the copolymers obtained by conventional radical polymerization, poly(VDF-*ter*-HFP-*ter*-$CF_2CF(SF_5)$) present a better thermostability. Moreover, as expected, the thermal stability of this poly(VDF-*ter*-HFP-*ter*-$CF_2CF(SF_5)$) increases with the molecular weight (Figure 6B). In contrast, poly(VDF-*ter*-HFP-*ter*-$CH_2CH(SF_5)$) terpolymers exhibits a poor thermostability (T_{dec} = 130−140 °C; note that T_{dec} corresponds to decomposition temperature, i.e., 10% of weight loss). Such a statement may be explained by the evaporation of the terpolymer before its degradation and may arise from the low molecular weight obtained. Hence, terpolymers based on a hydrogenated SF_5 comonomer exhibit lower molecular weights and hence undergo an easier evaporation before degradation.

The glass transition temperatures (T_g) of the different fluorinated terpolymers were assessed by differential scanning calorimetry (DSC), and the results are listed in Table 4. The T_g values of poly(VDF-*ter*-HFP-*ter*-$CF_2CF(SF_5)$) terpolymers were ranging from −52 to −42 °C without any other transitions (melting transition), showing an amorphous behavior and potential use for elastomer applications. As expected, T_g values increase vs molecular weights (Figure 6B) of the terpolymers and are close to T_g values previously obtained (Table 4). With such T_g values, and as reported in the literature, it is known that fluoropolymers, containing VDF and HFP base units only, exhibit an average T_g of −26 °C for high M_n. The comparison of this result to those obtained with a low CTA concentration indicates that the addition of SF_5 group leads to a decrease the T_g value (decrease of ca. −20 °C).

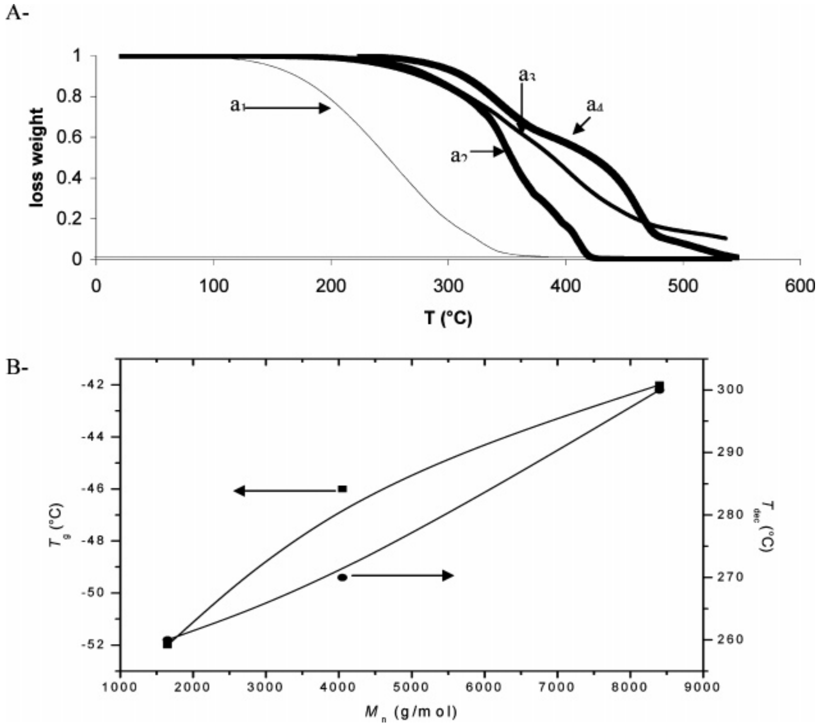


Figure 6. Thermal properties of poly(VDF-*ter*-HFP-*ter*-SF_5-monomer) terpolymers. (A) TGA thermograms of poly(VDF-*ter*-HFP-*ter*-SF_5-monomer) terpolymers, under air (10 °C/min); a_1 represents the poly(VDF-*ter*-HFP-*ter*-$CH_2CH(SF_5)$) terpolymer ($M_n = 600$ g/mol, run 5, Table 1), while a_2, a_3, and a_4 correspond to poly(VDF-*ter*-HFP-*ter*-CF_2CFSF_5) terpolymers with $M_n = 1650$ (run 2, Table 1), 4050 (run 3, Table 1) and 8400 g/mol (run 4, Table 1), respectively. (B) Glass transition (T_g) and decomposition (T_{dec}) temperature values of poly(VDF-*ter*-HFP-*ter*-CH_2CHSF_5) terpolymers vs their molecular weights.

Table 4. Thermal Properties of Poly(VDF-*ter*-HFP-*ter*-SF_5 Monomer) Obtained by Iodine Transfer Terpolymerization

			thermal properties	
runs	R_0	$M_n{}^d$ (g/mol)	T_g (°C)	T_{dec} (°C)
1[a]		10 000[f]	−50	280
2[b]	0.05	1650	−52	260
3[b]	0.02	4050	−46	270
4[b]	0.01	8400	−42	300
5[c]	0.05	260	−70[e]	120
6[c]	0.01	300	nd	130

[a] Without any chain transfer agent. [b] With $F_2C{=}CFSF_5$ as the comonomer. [c] With $H_2C{=}CHSF_5$ as the comonomer. [d] Determined by ^{19}F NMR. [e] This T_g value is not characteristic because it corresponds to T_g of a very low molecular weight. [f] SEC.

Conclusion

Monomers bearing a pentafluorosulfonanyl group (i.e., 1,1,2-trifluoro-2-pentafluorosulfanylethylene and pentafluorosulfanylethylene) were utilized in the attempted radical terpolymerization of hexafluoropropylene (HFP) and vinylidene fluoride (VDF) by iodine transfer polymerization in the presence of 1-iodoperfluorohexane. Under the same conditions, different behaviors were observed for both SF_5 monomers. Interestingly, when using $CF_2{=}CFSF_5$, a controlled radical terpolymerization was observed as evidenced by the good control of the molecular weights, i.e., the experimental molecular weights were in good agreement with the targeted ones for the first time and in good yields (80−90%). These terpolymers contain two chain ends (well-characterized by ^{19}F NMR), i.e. $-CH_2CF_2I$ and $-CF_2CH_2I$, while the other chain ends (i.e., $-CF_2CF(SF_5)I$, $-CF(SF_5)CF_2I$, $-CF_2CF(CF_3)I$, and $-CF(CF_3)CF_2I$) were not produced. Moreover, the functionality in $-CH_2CF_2I$ decreases vs the number of VDF units, but this functionality of terpolymer remains higher than that noted for poly(VDF)−I. Indeed, VDF, HFP and $F_2C{=}CFSF_5$ were incorporated in the terpolymer by ITP in the same proportion as that observed by conventional radical polymerization. Thus, this monomer could be terpolymerized by ITP successfully. Various poly(VDF-*ter*-HFP-*ter*-SF_5M) terpolymers were produced, the thermal stability (T_g and T_{dec}) of which depend on their molecular weights. Their T_gs values, in the range of −52 to −42 °C, show that these terpolymers are original elastomers stable up to 250−300 °C. On the other hand, the latter monomer, pentafluorosulfanylethylene, behaved differently, since it does not terpolymerize under ITP conditions, the yields being poor (ca.10−20%). Furthermore, experimental and targeted molecular weights were far from each other and confirm the poor control of this terpolymerization. In addition, $C_6F_{13}CH_2CHISF_5$ monoadduct produced as a byproduct, and could not reinitiate a further the terpolymerization. This could arise from a C−I bond that is not labile enough to enable a transfer in the radical polymerization but was not able to undergo a dehydroiodination to lead to $C_6F_{13}-CH_2{=}CHSF_5$. Furthermore, the formation of terpolymers bearing $-CF_2H$ end group attributed to a transfer reaction also induced a lack of control of the terpolymerization and favored short chain lengths. Further work is in progress regarding the synthesis of block copolymers based on $F_2C{=}CFSF_5$ monomer.

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Supporting Information Available: Text giving additional data in the Experimental Section and schemes of ITP mechanism, figures showing the ^1H and ^{19}F NMR spectra of poly(VDF)−I and poly(VDF-*ter*-HFP-*ter*-SF_5M) terpolymers and DSC curves, and tables of ^1H and ^{19}F NMR assignments of poly(VDF-*ter*-HFP−SF_5M) terpolymers. This material is available free of charge via the Internet at http://pubs.acs.org.

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