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Robust and Operationally Simple Synthesis of Poly(bis(2,2,2-trifluoroethoxy) phosphazene) with Controlled Molecular Weight, Low PDI, and High Conversion

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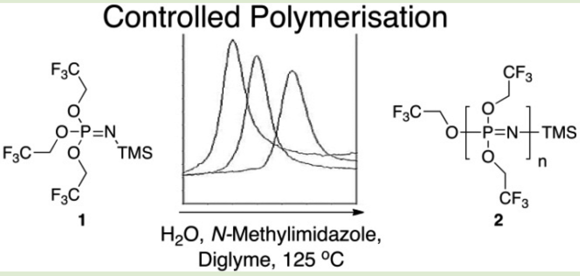
Supporting Information

ABSTRACT: Synthetically straightforward conditions have been developed for the preparation of poly(bis 2,2,2-trifluoroethoxy)-phosphazene with low PDI (<1.15) at high conversion (75–99%) and on a multigram scale. A combination of ^{31}P NMR and GPC analyses demonstrate that molecular weight increases linearly as a function of monomer consumption, exhibiting first order kinetics with respect to monomer concentration up to high monomer conversion. Thus, the molecular weight can be controlled by varying the initiator (H_2O) to monomer ratio.

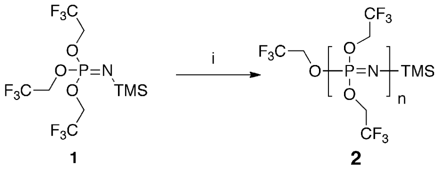


Poly(organophosphazene)s are macromolecules that contain a backbone of alternating phosphorus and nitrogen atoms with the following general formula: $[-N{=}PR_2-]_n$.[1] It has been shown that varying the nature of the pendent side group, R, enables the rapid synthesis of many hundreds of structurally distinct polymers that possess a diverse range of properties. Thus, poly(organophosphazene)s have become one of the most widely studied families of polymers with entirely inorganic mainchains, and derivatives of these materials have shown promise in applications as diverse as lubricants,[2] fuel cell membranes,[3] and biomedical applications.[4−7]

Industrial scale synthesis of poly(organophosphazene)s is achieved through the ring-opening polymerization (ROP) of the cyclic trimeric species, cyclohexaphosphazene $(-N{=}PCl_2)_3$ to deliver the hydrolytically unstable prepolymer, polydichlorophosphazene $(N{=}PCl_2)_n$.[8,9] Subsequent substitution of the chloride residues, by an organic nucleophile, results in the targeted poly(organophosphazene). Although this method can result in the synthesis of high molecular weight material ($M_n \approx 10^6$ Da), it suffers from several deficiencies, including high polymerization temperatures (260 °C), lack of control over molecular weight, and high PDIs (≈10). In addition, incomplete substitution of the halogen groups results in hydrolytically instable products and ROP cannot deliver complex polymer architectures such as block copolymers.

Efforts to overcome the problems associated with ROP synthesis of poly(organophosphazene)s have resulted in several condensation polymerization routes to these interesting materials. Early examples of these reactions were published by Flindt and Rose,[10] and the Neilson group[11] who showed that polymerization of phosphoranimines[12] delivered poly(organophosphazene)s with molecular weights in the range of $M_n \approx 10^5$ Da with PDIs < 3 at temperatures below 200 °C, albeit over extended reaction times (2 days). Subsequent work by Matyjaszewski and co-workers has demonstrated that tetrabutylammonium fluoride (TBAF)[13−17] and *N*-methylimidazole[17] can initiate the anionic polymerization of a trimethylsilyl phosphoranimime monomer (**1**, Scheme 1).

Scheme 1. Synthesis of Poly(bis(2,2,2-trifluoroethoxy)phosphazene) (2) from Phosphoranimine (1)[a]



[a]Reaction conditions: (i) Diglyme, *N*-methylimidazole, H_2O, 125 °C.

This procedure results in relatively high molecular weight polymers (10^4 Da) at high conversions (>95%) and block copolymers with PDIs between 1.3 and 2.3 at 95 °C in less than 4 h.[16] Most recently, Allcock and Manners have disclosed a low temperature (<35 °C), cationic, "living" synthesis of poly(dichlorophosphazene)[18,19] and poly(organophosphazene)s.[20−27] This mild procedure permits the synthesis of polymers with targeted molecular weights, narrow molecular weight

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distributions (PDI < 1.2), and typical isolated yields of over 90% after a 4 h reaction time. The methodology has been harnessed in the synthesis of materials with complex architectures including block copolymers[20−27] and star polymers with multiple poly(organophosphazene) arms.[27]

In this communication we describe a robust method for producing the versatile polymer poly(bis 2,2,2-trifluoroethoxy)-phosphazene) on a multigram scale. Polymerization proceeds in commercial grade solvents at readily accessible temperatures (125 °C). This new method[29] shows many of the characteristics of a living polymerization, including molecular weight control by varying the initiator to monomer ratio, low PDI (<1.15), and first order polymerization kinetics.[30]

During our investigations into the polymerization of **1** using similar conditions to those detailed by Matyjaszewski and co-workers,[17] it was found that the addition of a small quantity of water[28,29] resulted in the formation of poly(bistrifluoroethoxy phosphazene) (**2**, Scheme 1).[28] The isolated polymeric product (**2**) had a low PDI (<1.15), as determined by GPC analysis, suggesting that the reaction was proceeding through a living-type polymerization.[30]

To investigate this polymerization further, a stock solution of monomer **1** and *N*-methylimidazole (0.02 equiv) in diglyme was prepared. Five independent reactions were carried out, four of which contained decreasing ratios of monomer (**1**) to distilled water (16, 32, 64, and 125 equiv of **1**/H_2O) in addition to a fifth, control experiment that contained no added water. The solutions were heated to 125 °C and monitored by ^{31}P NMR at regular intervals for up to 11 h (Figure 1A; for spectra of all water initiated reactions, see the Supporting Information (SI)). The progress of the reactions was readily observed by ^{31}P NMR by comparing the relative intensities of the resonances for the monomer (**1**, −11.8 ppm) to that of the polymer (**2**, −8.4 ppm; Figure 1B).

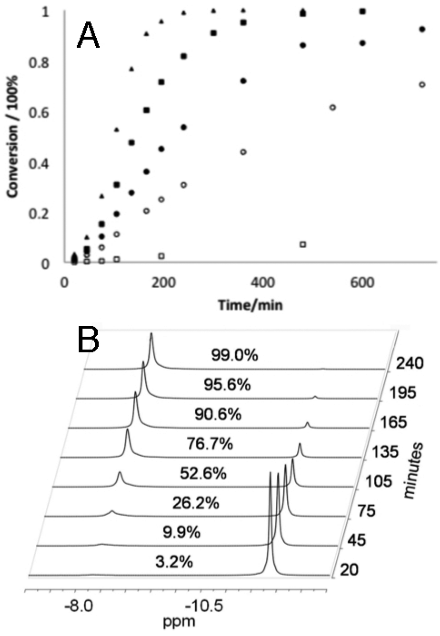

Figure 1. (A) Plots of the conversion of monomer (**1**) to polymer (**2**) as a function of time for reactions containing the following ratios of monomer (**1**) to water: □ 1:0; ○ 125:1; ● 64:1; ■ 32:1; ▲16:1. (B) Example of ^{31}P NMR spectra of percentage conversion with increasing reaction time where **1**/H_2O is 16:1.

For the reaction where no water was added (Figure 1A), monomer conversion to polymer remained below 10% even at extended reaction times (up to 500 min). For the four remaining reactions, where water was added to initiate the polymerization, an initial lag time of about 10 min was observed between the start of heating and the onset of polymerization. Presumably this is a consequence of the time required to reach the polymerization temperature. After the onset of polymerization, the rate of monomer conversion gradually decreases with time as monomer (**1**) is consumed, behavior that is consistent with a controlled (or "living") polymerization mechanism.[30]

After acquisition of the ^{31}P NMR spectra, each sample was quenched by freezing to −18 °C and subjected to GPC analysis to allow the evolution of molecular weight for the polymers to be determined as a function of monomer conversion. These data are plotted in Figure 2A. A selection of typical eluograms for **1**/H_2O ratio 125:1 shown in Figure 2B (for selected GPC eluograms of all water initiated reaction see SI). For each polymerization, regardless of the quantity of water added, the molecular weight is directly proportional to conversion, indicating a controlled polymerization process.

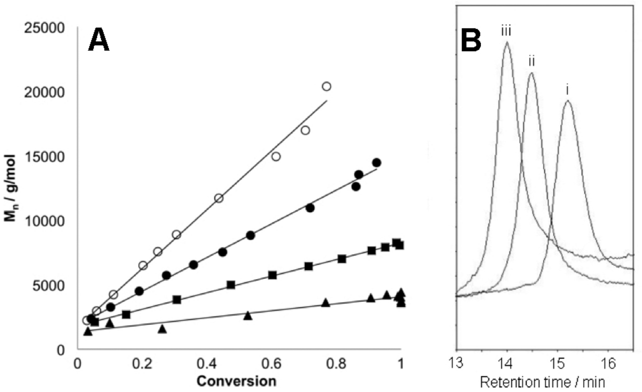

Figure 2. (A) Plot of M_n (determined by GPC analysis) as a function of monomer (**1**) conversion (measured by ^{31}P NMR analysis) for polymerization reactions containing the following ratio of **1**/H_2O: ○ 125:1; ● 64:1; ■ 32:1; ▲16:1. (B) Overlay of GPC eluograms showing the evolution of molecular weight with conversion for **1**/H_2O ratio 125:1 at 20, 44, and 70% conversion for eluograms i, ii, and iii, respectively.

Table 1 shows molecular weight data for the isolated polymers at high conversions (77−99%). In all cases where water was added to the reactions, the polydispersity of the

Table 1. Molecular Weight and Conversion Data for the Polymers Produced from Varying Ratios of Water to Monomer (1)

1/H_2O	time (h)	conversion %[a]	M_n[b] (Da; theor.)	M_n[c] (Da; GPC)	PDI[c]
1:0	79	95	N/A	22000	1.45
16:1	4	99	4000	4100	1.13
32:1	8	99	7900	9100	1.10
64:1	12	92	14000	17000	1.15
125:1	15.5	77	24000	25000	1.13

[a] Measured by ^{31}P NMR analysis. [b] Calculated from the initial monomer to water ratio at the measured conversion. [c] GPC analysis in THF relative to PS standards.

resultant polymers was low (≤1.15). Moreover, molecular weight could be controlled by simply varying the initial monomer to initiator ratio. For all four water-initiated examples, the observed molecular weight of these polymers was within 15% of that calculated (assuming each molecule of water cleanly initiates the propagation of one polymer chain). In comparison, the polymer produced under essentially anhydrous conditions only reached high conversion (95%) at greatly extended reaction times (>3 days) and exhibited a PDI of 1.45. This result suggests that the polymerization proceeds through a different reaction mechanism compared to when polymerization is initiated by water.

A key characteristic of living polymerizations is that the reaction must follow first order kinetics with respect to monomer concentration. Figure 3A shows a plot of ln($[M_0]/[M_t]$) as a function of time for the reaction where $1/H_2O$ was 32:1 with respect to monomer concentration, as measured by ^{31}P NMR spectroscopy. After an initial lag time, consistent with the time required to reach the polymerization temperature, the reaction follows strict first order kinetics, characteristic of a controlled polymerization mechanism.[30]

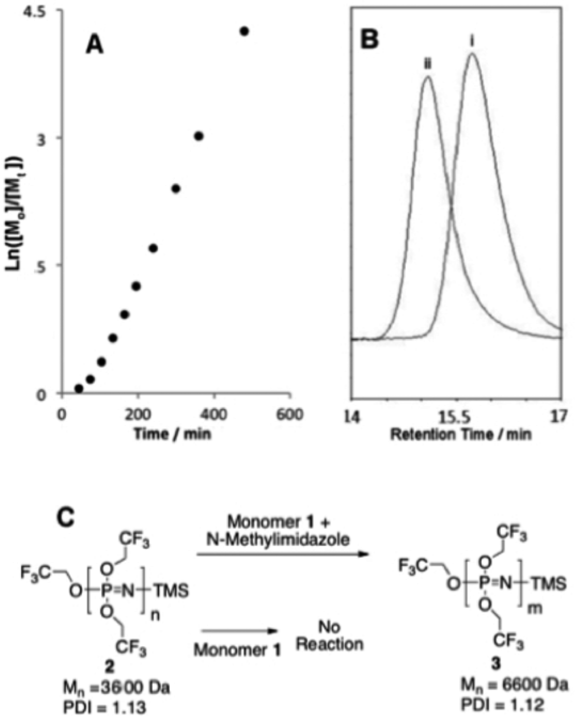

Figure 3. (A) Kinetic study of the polymerization where **1**/H_2O is 32:1. $[M_t]$ and $[M_0]$ are monomer concentration at time = "t" and time = 0, respectively (determined by ^{31}P NMR). (B) Overlay of GPC eluograms for (i) polymer (**2**) produced from a **1**/H_2O ratio 16:1, 3 h reaction time, M_n = 3600 Da, PDI = 1.13; (ii) polymer reinitiated from an isolated sample of polymer **2** (M_n = 6600 Da, PDI = 1.12 after 2.5 h further heating). (C) Scheme for reinitiated polymer synthesis.

First order kinetics were observed for monomer consumption for all four concentrations of water initiator studied (see SI). The reaction rate (k) for each of the reactions was determined from the slope of the plots to be in the range 0.0017 to 0.030 $\min^{-1}$. Moreover, a plot of the ln$[k]$ for each reaction versus ln$[H_2O]$ results in a straight line from which the slop indicates the reaction is of order 1.4 with respect to initial water concentration. A related series of rate experiments were conducted using fixed concentration of H_2O but varying concentrations of N-methylimidazole (see SI). Changing the initial concention of N-methylimidazole by an order of magnitude had little effect on the rate of the reaction. The order of reaction established as approximately 0.14 with respect to this reagent.[31]

To give an initial insight into the reaction mechanism, a polymerization was followed by ^1H NMR spectroscopy to allow the change in chemical environment of the TMS residues to be investigated. As the reaction proceeds, the signals corresponding to the TMS group on monomer **1** decreases while there is clear evidence for the formation of CF_3CH_2O-TMS (see SI). This can be accounted for by considering that the polymerization follows a similar reaction mechanism proposed by Matyjesewski and co-workers for their related TBAF initiated conditions.[13,16] In this case, rapid initiation by water hydrolysis of monomer **1** could generate an anionic propagating species (a phosphazene anion[16]). Subsequent attack of phosphazene anion on the phosphorus atom of a second monomer liberates trifluoroethoxide and results in a TMS terminated dimer, from which propagation may only proceed when the TMS end group is removed by the liberated trifluoroethoxide anion.

In an effort to demonstrate the utility chain end, a sample of polymer **2** with M_n = 3600 Da, PDI = 1.13 (Figure 3B, eluogram i, produced from **1**/H_2O = 16:1) was redissolved in diglyme to which was added a fresh batch of monomer **1**. Heating the solution to 125 °C did not result in further monomer conversion as observed by ^{31}P NMR analysis. However, addition of the stock solution of monomer (**1**) containing 0.02 equiv N-methylimidazole to polymer **2** followed by heating to 125 °C resulted in rapid monomer conversion, and after 2.5 h the reaction was stopped and the product was isolated by precipitation (Figure 3C). The reinitiated polymer exhibited a monomodal molecular weight distribution by GPC analysis with M_n = 6600 Da and a PDI of 1.12 (Figure 3B, eluogram (ii)), a significantly higher molecular weight than that of the starting material (for full experimental procedure, see SI). An overlay of the GPC eluograms for the initial polymer (Figure 3B, eluogram (i)) and the final product (Figure 3B, eluogram (ii)) clearly shows complete loss of the starting material, demonstrating that polymerization was reinitiated from the termini of the polymer chains. The increase of molecular weight by 3000 Da over a period of 150 min is also in line with the kinetic data shown for **2** with an approximate conversion of 80% being equivalent to ~2900 Da.

This paper has detailed the controlled, multigram scale synthesis of poly(bis (2,2,2-trifluoroethoxy)phosphazene) (**2**) with a molecular weight of up to 25 kDa and narrow PDI (≤1.15). The polymerization is initiated by water with a catalytic amount of N-methylimidazole at easily accessible temperatures (125 °C). Through a combination of ^{31}P NMR spectroscopic and GPC analyses we have demonstrated (i) the molecular weight of the polymer increases linearly with respect to consumption of monomer up to high conversion; (ii) molecular weight can be predicatively controlled by varying the ratio of initiator to monomer; and (iii) the reaction exhibits first order kinetics with respect to monomer concentration. Although the nature of the end group in the isolated polymer has not been positively identified, we have shown that polymerization can be reinitiated from an isolated sample, raising the possibility of producing block copolymers which we are currently investigating.

Our methodology differs from previously reported conditions to produce polymer **2** from phosphoranimine **1** in that it delivers polymers with tunable M_n and PDIs < 1.15 using H_2O as an initiator.[13−17] Although this synthesis requires higher temperatures (125 °C) than required for the living polymerization studied principally by Allcock and Manners[18−27] (35 °C), it benefits from the accessibility of the starting monomer (**1**), which can be produced in one step from commercially available starting materials compared to the two steps required for the synthesis of bromo(silylamino-(phosphoranimines)) monomers typically used in their work.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Synthesis and characterization of monomer **1**, full experimental details and polymerization procedures, ^{31}P NMR spectra of conversion of monomer to polymer as a function of time, and selected GPC eluograms showing molecular weight evolution as a function of time. Plots used to establish the rate and order of reaction with respect to H_2O and *N*-methylimidazole. Partial ^{1}H NMR spectra showing polymer conversion as a function of time. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.
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