Reactions of living polytetrahydrofuran with amines: 3. Secondary amines

D. B. Hartley, M. S. Hayes and D. H. Richards
Propellants, Explosives and Rocket Motor Establishment, Ministry of Defence, Waltham Abbey, Essex EN9 1BP, UK

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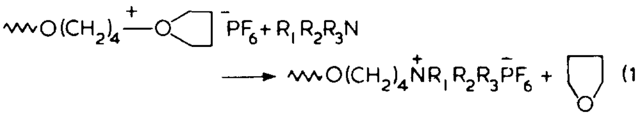
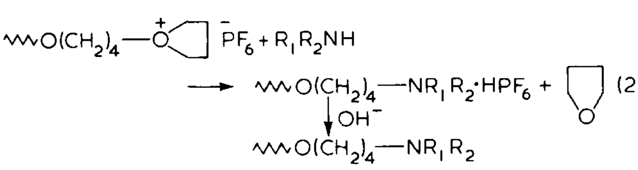
Poly THF with terminal tertiary amine groups has been prepared from the following secondary amines: diethylamine, dicyclohexylamine, piperidine, diphenylamine and carbazole. The reaction of living polymer with aliphatic amines is rapid, but the slower reaction of the aromatic amines necessitates their prior conversion to the lithium salt. The products from the aliphatic amines elute somewhat later than expected from Styragel g.p.c. columns, but with an unchanged distribution, while polymer terminated by the aromatic amines behaves noormally. Poly THF terminated with diethylamine has been reacted with further living poly THF to yield a homopolymer with a quaternary ammonium grouping along the chain. It is also argued from g.p.c. traces that the same polymer tertiary amine quaternizes with a polystyrene bromide to give a block copolymer which fails to elute from the columns.

INTRODUCTION

Earlier papers in this series[1,2] have shown that living cationically polymerized polytetrahydrofuran (polyTHF) reacts with tertiary amines under mild conditions to form quaternary ammonium salt terminated polymers (equation 1). The rate of reaction is a direct function of the basicity of the amine, the reactivity of the heterocycles being in the order 4-ethylpyridine > pyridine > isoquinoline > quinoline > acridine, and of the aliphatic amines being in the order triethylamine > tributylamine > diethylaniline. The most basic reagents react under equimolar (10^{-2} M) conditions within a minute or so at −10°C whilst reaction with acridine is incomplete after several hours. Quantitative conversion with the latter can, however, be achieved in a short time by using excess acridine, and it has been shown in all cases that the quaternary ammonium salt is irreversibly formed.


(1)

It seemed probable that this type of replacement reaction could be extended to amines other than tertiary, and here we report on studies carried out on the reaction of living polyTHF with secondary amines. The reaction was expected to result in the initial formation of polymer possessing terminal groups which were the acid salts of tertiary amines, and which could be subjected to alkali to yield polymer with tertiary amine terminal groups (equation 2). Such a reaction would be of synthetic interest since the product could then in principle be submitted to reaction with further living polyTHF (equation 1) to generate a polymer possessing a quaternary ammonium group at a point along the chain determined by the relative molecular weights of polyTHF used.


(2)

Materials similar to the latter have been prepared previously by a one or two stage reaction with diamines such as N,N,N′,N′-tetramethylethylene diamine and 4,4′-bipyridyl[2]. In this system, however, chain linking was effected by quaternization at each of the tertiary nitrogens

$$(\sim\!\sim\overset{+}{N}R\overset{+}{N}\sim\!\sim)$$

and, unlike the proposed product, neither nitrogen was attached to more than one polymer chain, so different steric considerations obtain.

Here we consider firstly the synthesis of polyTHF with terminal tertiary amine groups, and then the quaternization of this product with living polyTHF and with polystyrene possessing a terminal bromine atom.

EXPERIMENTAL

Materials

Tetrahydrofuran (THF), silver hexafluorophosphate, *p*-methylbenzyl bromide, and n-butyl lithium were used as described previously[1].

Diethylamine and piperidine (BDH) were purified by fractional distillation under nitrogen from calcium hydride, and diphenylamine (BDH) and carbazole (Koch-Light) were recrystallized respectively from 60–80 petroleum ether and benzene. Dicyclohexylamine (BDH) was used as supplied.

Bromine-terminated polystyrenes (*MW* = 1800) were prepared as described elsewhere[3,4] by the reaction of living monofunctional polystyrene with excess bromine or *m*-xylylenedibromide.

Preparation of polyTHF—tertiary amine adduct

The termination of living polyTHF by secondary amines was studied by methods similar to those employed

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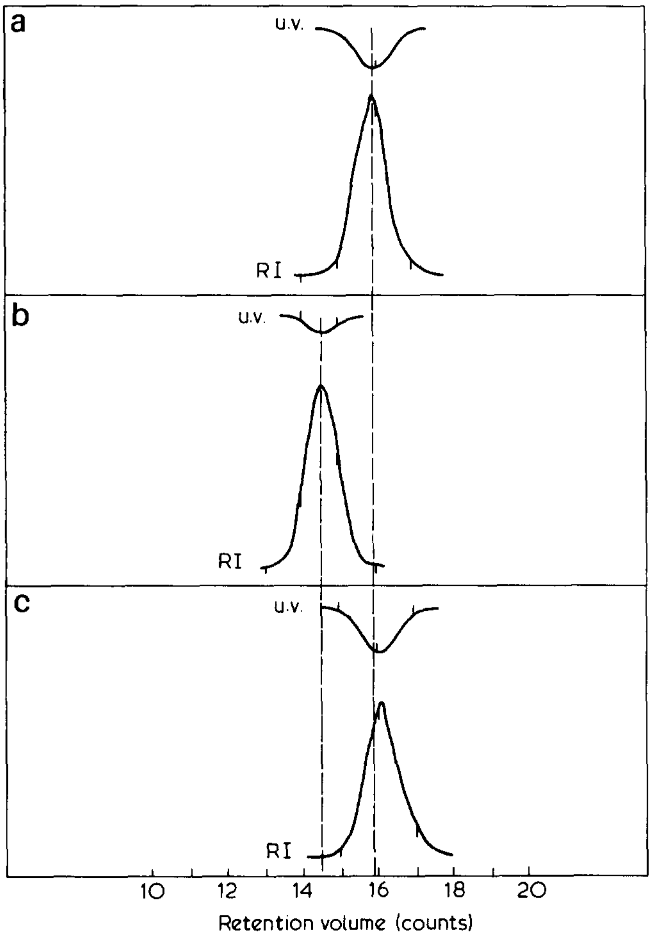


Figure 1 G.p.c. traces of reaction of living polyTHF with diethylamine (1:3). (a) Low molecular weight control, (b) high molecular weight control, (c) product after 2 h reaction; u.v., 64x; RI, 16x

previously[1,2]. Using a solution of the living polymer, 10^{-2} M, *MW* 3000–4000, prepared from $AgPF_6$ and *p*-methylbenzylbromide in THF, the amine or its lithium salt (from reaction of the amine with butyl lithium in THF solution) was injected, and allowed to react at −10°C for 2–3 h before working up from a sodium carbonate–methanol mixture. This is sufficient time to allow any unreacted polymer to grow to significantly higher molecular weight, and from comparison of the gel permeation chromatographic (g.p.c.) trace of this product with those of samples of living polymer taken from a control solution at the beginning and end of the experiment and terminated with methanol, it was possible to determine whether polymerization was terminated by the amine.

The products were also subjected to analysis by ^{1}H and ^{13}C n.m.r. spectroscopy to confirm the structures of the end groups formed.

Gel permeation chromatography (g.p.c.)

The g.p.c. equipment used and the method of calculating molecular weights where required were the same as described in Part I. Injection concentrations were normally in the range 0.1% to 0.3% w/v.

Nuclear magnetic resonance spectroscopy (n.m.r.)

^{1}H and ^{13}C n.m.r. spectra were recorded at 100 MHz on a Jeol PS100 Spectrometer using approximately 20% solutions in deuterochloroform with tetramethylsilane as an internal standard.

Reaction of living polyTHF with diethylamine-terminated polymer

Preparation of polyTHF-diethylamine. p-Methylbenzylbromide (0.615 g; 3.32 m mol) was added at −10°C to a stirred solution of silver hexafluoro phosphate (0.791 g; 3.13 m mol) in THF (150 ml) under nitrogen. The solution was maintained at −10°C for 1 h, filtered, and allowed to polymerize for a further $\frac{1}{2}$ h. A sample was then withdrawn into methanol to provide polyTHF reference material, and diethylamine (0.65 ml; 6.3 m mol) was simultaneously added to the remainder. After 15 min the amine solution was treated with a small excess of KOH in methanol 0.05 M) and worked up from ether solution after washing with an aqueous solution containing Analar grade magnesium sulphate to prevent emulsion formation. The product eluted 0.2 counts later than the methoxy terminated reference in the g.p.c. trace, and its molecular weight (4600) was derived from the g.p.c. molecular weight of the latter. It was pumped for 8 days under high vacuum before reacting with further living polymer.

Quaternization of polyTHF—diethylamine with living polyTHF. A solution of living polyTHF, molecular weight 2500, (10 ml; 0.2 m mol) was added to a stirred solution of polyTHF-diethylamine, molecular weight 4600 (0.92 g; 0.2 m mol) in THF (9.35 ml) under nitrogen at −20°C. The mixture was allowed to warm to −10°C and samples were withdrawn into methanol at 15 min and 4 h, and compared with samples of living polymer polymerizing separately in the same bath. The polymers were isolated by removal of solvent followed by overnight pumping.

RESULTS AND DISCUSSION

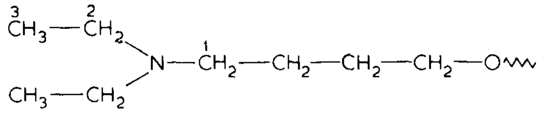
Synthesis of polyTHF possessing tertiary amine terminal groups

The reactions of living polyTHF with three aliphatic and two aromatic secondary amines were examined, and are considered separately below.

Diethylamine. In a typical experiment, living polyTHF was reacted with a 3-fold molar excess of amine. The g.p.c. trace of the isolated product was compared with those of the two methanol terminated polyTHF standards, one terminated when the amine was introduced to the living polymer (low molecular weight) and the other when the reaction was stopped about 2 h later (high molecular weight). All three traces are shown in *Figure 1*. It is apparent that the retention time of the aminated polymer is slightly greater than, but very close to that of the low molecular weight control. Further, the peak shape of this material is symmetrical and narrow, with no indication of a high molecular weight component. Thus it may be inferred that rapid quantitative reaction has occurred under these experimental conditions. Similar results were also obtained when the amine was converted to the lithium salt prior to addition to the living polymer, consistent with the rapid reaction expected of such strong nucleophiles.

Examination of the product by ^{1}H n.m.r. spectroscopy indicated the presence of a diethylamine moiety, but was unable to confirm irrefutably the tertiary amine structure. ^{13}C spectroscopy with its much greater range of chemical shifts was able to do so, and *Table 1* shows the good agreement obtained between the observed chemical shifts

Table 1 Calculated and observed chemical shifts of diethylamine terminated polyTHF



Neighbouring Groups	Carbon 1 No	Carbon 1 Shift	Carbon 2 No	Carbon 2 Shift	Carbon 3 No	Carbon 3 Shift
α-carbon	1	+9.1	1	+9.1	1	+9.1
β-carbon	3	+28.2	2	+18.8	0	0
γ-carbon	3	−7.5	2	−5.0	2	−5.0
α-nitrogen	1	+29.3	1	+29.3	0	0
β-nitrogen	0	0	0	0	1	+11.3
α-branch	1	−2.5	1	−2.5	0	0
arbitrary constant	1	−2.6	1	−2.6	1	−2.6
calculated (ppm)	+54.0		+47.1		+12.8	
observed (ppm)	+52.5		+46.5		+11.9	

and those calculated for the expected structure using published chemical shift data.[5]

These experiments therefore demonstrate that diethylamine terminated polyTHF may be prepared by the direction reaction of living polymer with excess amine.

Dicyclohexylamine and piperidine. These reagents possess basicities similar to that of diethylamine and so were anticipated to behave in similar ways. Experiments identical to those described for diethylamine were carried out, and analogous results were obtained for both reagents. With each amine the g.p.c. trace showed a single narrow symmetrical product peak at a retention time slightly longer than that of the low molecular weight control (compare with *Figure 1*).

Diphenylamine. The addition of a 3-fold molar excess of diphenylamine to living polyTHF resulted in the termination of only a fraction of the propagating chain ends after 2 h at −10°C. The g.p.c. traces of the isolated material and the respective controls are reproduced in *Figure 2a* to *c*. A number of significant features are evident in these traces, which recall the polyTHF–acridine system described in Part 2: (i) the product has its peak at a retention time close to that of the high molecular weight control, (ii) the product trace, unlike those of both controls, is not symmetrical but possesses a tail at high retention time, and (iii) the product exhibits enhanced u.v. absorption, the peak of which is at significantly higher retention time than that of the RI trace.

These observations indicate that the reaction with diphenylamine is slow, the bulk of the polyTHF chains having retained their oxonium terminal groups and continued to polymerize normally. The increased u.v. absorbance, however, confirms that some reaction has taken place to yield diphenylamine end groups. Further, the positioning of this u.v. peak at a molecular weight lower than that corresponding to the RI maximum suggests that little or no exchange of amine group occurs between the terminated and living chains during the time scale of the experiment. This slowness of the reaction was not unexpected since similar behaviour had been previously observed between living polyTHF and N,N-diethylaniline.

Although the reaction could probably have been pushed closer to completion by using higher reagent concentrations, an alternative approach to a narrow molecular weight distribution product was to convert the amine to its lithium salt. The g.p.c. trace of the product resulting from use of this reagent in threefold excess is shown in *Figure 2d*; is shows a narrow distribution in the

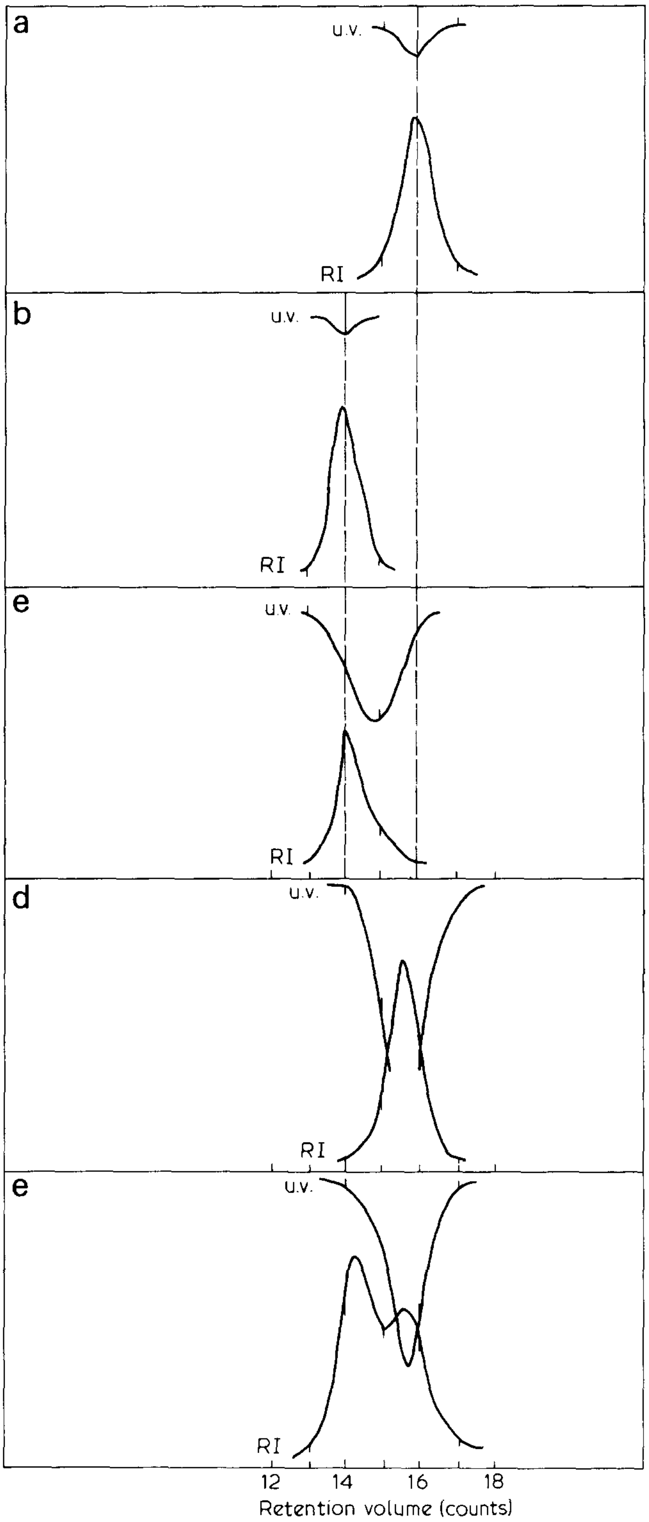
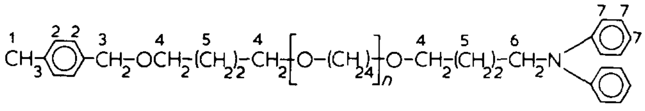


Figure 2 G.p.c. traces of reaction of living polyTHF with diphenylamine. (a), (b) and (c) low molecular weight control (LMWC), high molecular weight control (HMWC) and product after 2 h reaction respectively, u.v., 64x; RI, 16x; (d) reaction of living polyTHF with lithium diphenylamine (1 : 3), LMWC = 15.6 counts, HMWC = 14.1 counts, u.v., 128x; RI, 8x; (e) reaction of polyTHF with diphenylamine–lithium diphenylamine mixture (1 : 1 total amine), LMWC = 15.8 counts, HMWC = 14.1 counts, u.v., 128x; RI, 8x

Table 2 Assignment of the absorptions in the ^1H n.m.r. spectrum of diphenylamine terminated polyTHF (in deuterated chloroform with tetramethylsilane as internal standard)



Peak position (ppm)	Assignment	Peak position (ppm)	Assignment
7.33	chloroform	3.40	4
7.22	2	2.50	6
7.20	7	2.35	1
6.90	7	1.60	5
4.50	3		

position of the low molecular weight control, with the peak in the u.v. signal now coinciding with that in the RI trace, clearly indicating that a rapid reaction had been achieved in this way.

Further experiments were carried out in which living polyTHF was introduced to an equimolar solution of diphenylamine partially reacted with butyl lithium. The g.p.c. trace of the product resulting after 2 h is shown in *Figure 2e.* The RI trace exhibits a double peak with positions corresponding to those of the two controls, and the u.v. trace records a single peak coincident with the low molecular weight control. This result quite clearly confirms the relative rapidity of reaction with the lithium salt, and establishes the lack of exchange of amine between the terminated product and living polyTHF.

The presence of diphenylamine end groups in the product was established by ^1H n.m.r. spectroscopy on material isolated from excess amine by fractionation by g.p.c. The assignment of absorptions is given in *Table 2*, the existence of polymer linked amine being proven by the

$$-\underline{CH_2}-N\!<$$

signal at 2.50 ppm.

Carbazole. Isolation and g.p.c. analysis of the product resulting from the introduction of 3-fold molar excess of carbazole to living polyTHF at -10°C showed no evidence of termination after 2 h. The product trace was narrow and symmetrical with no increased u.v. absorbance, and possessed a retention time close to that of the high molecular weight control.

Experiments were therefore carried out using 3-fold molar excess of the lithium salt and, as with similar experiments involving diphenylamine, the product gave a narrow symmetrical RI trace with the peak at a retention time corresponding to the low molecular weight control. The presence of a carbazole adduct was signalled by the strong u.v. absorbance at the same retention time, and the expected amine structure was confirmed by ^1H n.m.r. analysis of the purified product. The assignment of absorptions is given in *Table 3*, and the formation of the adduct is established by the

$$-\underline{CH_2}-N\!<$$

absorption at 2.85 ppm.

General

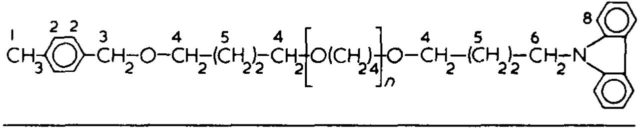
The above results follow a pattern similar to that observed with the tertiary amines[2] where the aliphatic amines were also found to be more reactive than the aromatic, suggesting that the observed rates are determined by the relative basicities of the amine in an organic medium (THF). It has also been shown that, whereas to maintain a sharp molecular weight distribution of aminated product with a slow-acting tertiary amine requires a high concentration of amine, a preferable approach to increasing the reaction rate of a secondary amine is to first convert it to its lithium salt.

It is of interest to note that no evidence of further addition of living polyTHF to the polymeric products was obtained in the experiments carried out. This could occur in principle by equilibration of the HPF_6 present in the product as first formed (equation 2) with unreacted secondary amine, leaving the resulting free polymer tertiary amine base available for attack by living polymer. Loss of acid in this manner from the initial products appears to be responsible for the attachment of one and two additional polymer chains which can be observed in the products from living polyTHF with primary amines and ammonia[6]. The apparent failure of the reaction to extend to the formation of quaternary salts as co-products in the present cases may also indicate that the tertiary amine terminated polymers are more basic toward Brønsted acids than the reactant amines, and therefore remain as the acid salts. It should, however, be noted that the recognition of quaternary ammonium salts of polyTHF by g.p.c. is likely to be complicated by column adsorption and in small amounts they could well have been obscured by peak overlap with the main reaction product.[1,2].

As observed with most of the quaternary ammonium salt products of polyTHF[1,2] some of the tertiary amine polymers were also found to display anomalous g.p.c. behaviour in that the adducts derived from the aliphatic amines eluted about 0.2 counts later than the controls, while the aromatic amine derivatives showed no such effect. In detail, however, the behaviour diverges from that of the quaternary salts since the distributions remain symmetrical after reaction, and the tailing noted with the quaternary salts, which is a normal characteristic of column adsorption, is absent. A further distinction is that no dependence of the retention time of the polymer tertiary amines with injection concentration was found (measured only on the diethylamine terminated polymer). This behaviour more closely relates to that obtained with the few quaternary salts examined in which column interactions could be interpreted as being reduced owing to steric factors (acridinium and pyrazinium)[2].

The delays in elution recorded were shown not to be

Table 3 Assignment of the absorptions in the ^1H n.m.r. spectrum of carbazole terminated polyTHF (in deuterated chloroform with tetramethyl silane as internal standard)



Peak position (ppm)	Assignment	Peak position (ppm)	Assignment
8.10	8	2.85	6
7.40	7	2.35	1
7.20	2	2.10	acetone
4.45	3	1.60	5
3.40	4		

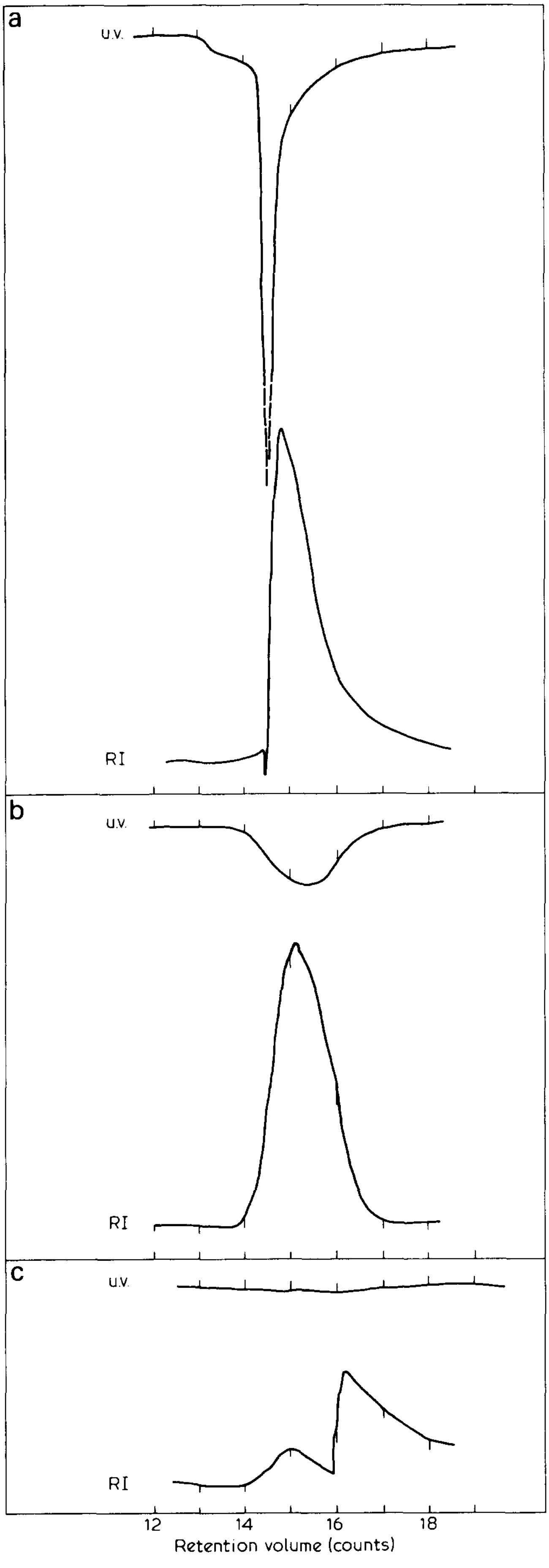


Figure 3 G.p.c. traces of quaternization of polyTHF-diethylamine by living polyTHF, (a) product after 15 min, injection concentration 0.14% w/v, u.v., 16x; RI, 4x; (b) initial composition, concentration 0.15% w/v, u.v., 16x; RI, 4x; (c) product after 15 min, injection concentration 0.05% w/v, u.v., 16x; RI, 2x

due to degradation, by the similarity of the elution profile of product taken 5 min after diethylamine addition with that of the reaction mixture some hours later.

Anomalous g.p.c. behaviour on polystyrene gels has previously been observed with small molecule amines, where positive and negative deviations from normal retention time were discussed in terms of hydrogen bonding (in the case of primary and secondary amines) and possible pore contraction, but effects observed due to the aliphatic or aromatic nature of the substituents could not be explained[7]. If the absence of tailing and of a concentration dependence of retention time in the polymer traces indicate that column adsorption is insignificant, then the longer retention times may be ascribed to the terminal aliphatic amine groups inducing a tighter conformation of the polymer coil than the methoxy-terminated derivatives.

Quaternization of polyTHF possessing tertiary amine terminal groups

PolyTHF terminated by secondary amines as described above offers interesting possibilities for coupling with other polymer blocks by quaternization on to the terminal nitrogen. The previous work with small molecule tertiary amines suggests that it may be used as a reagent to link with a second chain of living polyTHF, forming a homopolymer in which the position of the ionic nitrogen may be varied by suitable choice of reactant molecular weights. Block copolymers might also be prepared by reacting such tertiary amine terminated materials with other polymers possessing halide groups such as polystyrenes carrying terminal primary or secondary benzyl bromide units, which have been described elsewhere[3,4]. These two possibilities were explored using a diethylamine terminated polyTHF, which is likely to be one of the more reactive tertiary amine groupings prepared.

Quaternization by living polyTHF. The g.p.c. of the product obtained after 15 min reaction with living polyTHF shows a narrower distribution (*Figure 3a*) than that of an unreacted mixture of the same composition (*Figure 3b*) which embraces methoxy-terminated living polymer and polyTHF-diethylamine with individual elution volumes of 15.7 and 15.0 counts respectively. Tailing is however apparent at longer retention times which is not present in the reactants, and the unsymmetric trace resembles those typically obtained with quaternary ammonium salts of polyTHF formed from small molecule tertiary amines[1,2]. The retention time of the peak is less than that of both reactants indicating a higher molecular weight product, and a further indication that this has the expected quaternary salt structure is the 'spiking' observed in the u.v. trace, with a corresponding discontinuity in the RI signal. This has been encountered before with quaternary ammonium products of polyTHF[2], when it was considered to be particularly characteristic of those formed from the non-heterocyclic tertiary amines, though its cause is not understood.

Confirmation that reaction had occurred was obtained from the similarity of the trace of the product after 15 min (*Figure 3a*) with that after 4 h. The latter gave no evidence of any remaining living polymer which would have been resolved at about 13.1 counts by reference to a control solution run in parallel. The fact that the later trace was indistinguishable from the earlier one indicates that the reaction was essentially complete within 15 min.

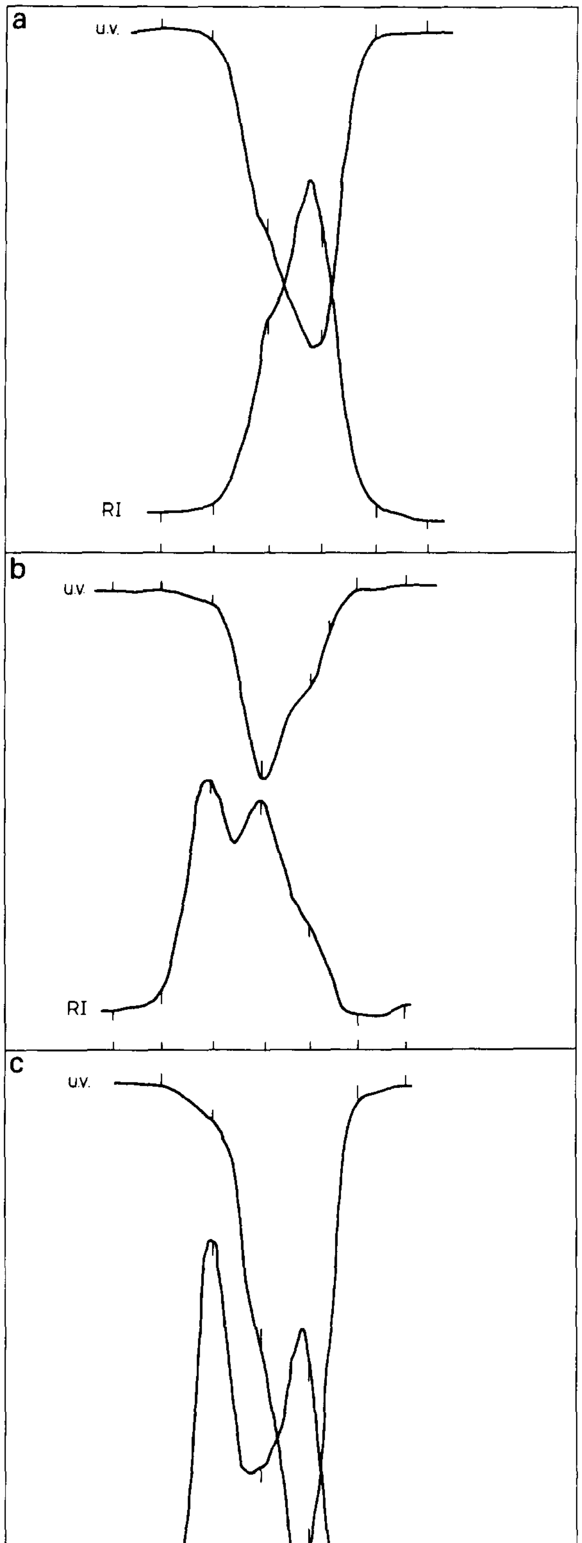
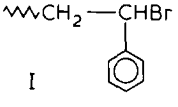


Figure 4 G.p.c. traces of quaternization of polyTHF–diethylamine by polystyrene bromide (II). (a) polystyrene bromide II, 0.1% w/v, u.v., 128x; RI, 8x; (b) product trace after 3 days, 1 g solution/100 ml, u.v., 64x; RI, 4x; (c) initial reaction mixture, 1 g solution/100 ml; u.v., 64x; RI, 4x

Finally, the product was established as a quaternary salt by observing the effect of injection concentration on the time to elution. The marked inverse dependence of retention time on concentration noted with quaternary products formed by reaction of living polyTHF with tertiary amines[1,2] has been ascribed to polar end group interactions with the column substrate. The same effect was found to obtain with the present product, the retention time decreasing to 14.3 counts with a 0.42% w/v injection, and increasing to 16.2 counts at 0.05% w/v and it is concluded that a similar ionic structural unit is formed.

The value of the retention time observed at the higher injection concentration also confirms the coupled nature of the product which would be expected to elute with a peak maximum near 14.2 counts on the basis of the reactant molecular weights, when the column adsorption sites approach saturation. At the lower concentration the later elution of the product interestingly reveals an additional underlying polymer fraction at 15.1 counts as shown in *Figure 3c*. This coincides with the position of the reactant amine, but the peak could also represent living polyTHF which would elute in approximately the same position if simply propagating during the 15 min reaction time. However, the presence of the peak at the same position in the 4 h product, also revealed using a reduced injection concentration, indicates that it almost certainly represents unreacted amine, and that inexact equivalences of reactants were in fact used.

Quaternization by bromide-terminated polystyrene. Quaternizations of the same diethylamine terminated polyTHF as used above were also attempted using polystyrenes terminating in a bromine atom either as a secondary benzyl bromide[3] (structure I) or as a primary benzyl bromide[4] (structureII). Both materials contained a proportion of unreactive material, comprising protonated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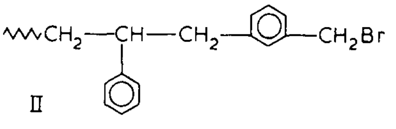
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polymer and coupled product of double molecular weight. The experiments were carried out at room temperature in dichloromethane at concentrations at which small molecule tertiary amine–organic halide quaternizations take place within a few hours, and the solutions were examined periodically by g.p.c. using a constant weight sample injection.

No sign of reaction with polyTHF–diethylamine was found in 78 days using the polystyrene with terminal structure I, but with polystyrene of structure II (*Figure 4a*) the g.p.c. trace shown in *Figure 4b* was obtained 3 days after mixing which remained unchanged subsequently. This differs from the starting mixture (*Figure 4c*) in both its intensity and the position of the main polystyrene component, recognised by the u.v. signal at 16.1 counts.

From the molecular weights of the reactants and the approximate composition of the polystyrene, determined from g.p.c. peak area after splitting out the bromine containing fraction as a polystyrene–polyTHF block copolymer of higher molecular weight,[4,8] it was estimated that a roughly 100% excess of polyTHF over brominated polystyrene was present in the initial mixture. The substantial reduction but not the elimination of the polyTHF peak near 15 counts can therefore be at least qualitatively consistent with its reaction with the bromide component of the polystyrene at 16.9 counts if the quaternary product has largely failed to elute. The non-reactive coupled material near 16 counts (compare with *Figure 4a*) comprising an estimated 45% of the original reactant would then be left as the main polystyrene component observed, and the shoulder at 16.9 counts would represent the protonated fraction.

The product trace thus offers strong evidence for the formation of a polystyrene–polyTHF block copolymer containing a quaternary ammonium linking group, and seems to give a clear indication that complete retention of charged polymers by the Styragel columns can occur under some conditions.

This conclusion is also consistent with results obtained on quaternizations involving small molecule halides where the polyTHF reactant peaks decrease in intensity with time without the appearance of identifiable quaternary products at longer retention times. This suggests that the halogen salts are more strongly held on the columns than the hexafluorophosphate salts described in Part II. However, the weak appearance of these quaternary products at what were probably low concentrations in the injected samples may reflect the existence of concentration thresholds below which they may be completely withheld by the Styragel[9], irrespective of the associated ion.

Lastly, the apparently large difference in reactivity of the two polystyrene bromides was unexpected since each had been found to be reactive with silver perfluorophosphate in producing copolymers with THF[3,4]. The difference in behaviour is not readily accounted for, but it suggests that an additional factor, involving the relative accessibilities of the two bromine atoms comes into play in reaction with another polymer molecule, which may be related to the mutual immiscibility of the two dissimilar polymer chains.

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REFERENCES

1 Cunliffe, A. V., Hartley, D. B., Kingston, S. B., Richards, D. H. and Thompson, D. *Polymer* 1981, **22**, 101

2 Cunliffe, A. V., Richards, D. H. and Robertson, F. C. *Polymer* 1981, **22**, 108

3 Burgess, F. J., Cunliffe, A. V., MacCallum, J. R. and Richards, D. H. *Polymer* 1977, **18**, 719

4 Burgess, F. J., Cunliffe, A. V., MacCallum, J. R. and Richards, D. H. *Polymer* 1977, **18**, 726

5 Stothers, J. B. 'Carbon–13 NMR Spectroscopy', Academic Press, (1972) 152

6 Cohen, P., Hartley, D. B., Richards, D. H. and Schue, F. unpublished results

7 Edwards, G. D. and Ng, Q. Y. *J. Polym. Sci. C* 1968, **21**, 105

8 Burgess, F. J., Cunliffe, A. V., Dawkins, J. V. and Richards, D. H. *Polymer* 1977, **18**, 733

9 Ambler, M. R. *J. Poly Sci. Polym. Lett. Edn.* 1976, **14**, 683