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Effect of Stannous Octoate on the Composition, Molecular Weight, and Molecular Weight Distribution of Ethylene Glycol-Initiated Poly(ε-Caprolactone)

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EFFECT OF STANNOUS OCTOATE ON THE COMPOSITION, MOLECULAR WEIGHT, AND MOLECULAR WEIGHT DISTRIBUTION OF ETHYLENE GLYCOL-INITIATED POLY(ε-CAPROLACTONE)

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Key Words: Stannous Octoate, Alcohol-Initiated Ring-Opening Polymerization, ε-Caprolactone

ABSTRACT

Bulk polymerizations of ε-caprolactone (CAP) were conducted at 120°C, with and without ethylene glycol (EG) as initiator, using varying concentrations of stannous octoate (SO) as catalyst. In the presence of EG, GPC showed that molecular weight (MW) was determined by the [CAP]/[EG] ratio and not by [SO] or the concentration of adventitious water brought into the reactor via the catalyst. Without EG, MWs were higher but decreased as [SO] was increased; polymerization rates were also lower, and the relationship between MW and conversion suggested the participation of both ring-opening and condensation polymerization. Late EG addition at high CAP conversion reduced MW to a level that was consistent with the [CAP]/[EG] ratio, regardless of the MW of the initial water-initiated polymerization. To aid in structural analysis of the polymers by NMR spectroscopy, two model systems were synthesized using [CAP]:[EG]:[SO] ratios of 0:2:1 and 4:2:1. Additional polymerizations were conducted at 80°C using anhydrous EG as initiator; three were charged with varying amounts of water (0.5, 1, and 2 moles/mole EG), three with EHA (0.025, 0.05, and 0.1 mole/mole EG), and one received no additional reagent. Monomer conversion (by ^1H NMR) vs. time curves showed that all three concentrations of water depressed the rate of polymerization relative to the control; however, the rate had begun to rise for the highest concentration of water. GPC indicated lower MW with increasing water, suggesting the rise in rate was caused by increasing total initiator (EG + H_20). All three concentrations of EHA depressed the rate relative to the control, and again the rate had begun to rise for the highest concentration. GPC indicated essentially no effect of EHA concentration on MW. Matrix-assisted laser desorption/ionization time-of-light mass spectroscopy confirmed that polymerizations conducted in the presence of water consisted of two separate distributions: difunctional chains of higher average MW containing an EG residue, and monofunctional chains of lower average MW containing a water residue (carboxylic acid end group). The control displayed a small fraction of water-initiated chains, which increased as the amount of added water increased. The presence of EHA increased the fraction of water-initiated chains relative to the control, but the concentration of EHA did not affect the fraction of water-initiated chains.

INTRODUCTION

In the last three decades, aliphatic polyesters that undergo degradation *in vivo* have been used for implantable drug delivery devices, [1-3] and surgical sutures, [4, 5] and more recently, environmentally degradable polyesters have been introduced as commodity molding plastics. Some important aliphatic polyesters include poly(lactide), poly(glycolide) and poly(ε–caprolactone). These polymers are synthesized via ring-opening polymerization through the use of compounds such as triphenyltin acetate, [6] tributyltin derivatives, [7] tin (II) salts [8] or tin (IV) compounds [9]. The detailed role of each of these compounds as either catalyst or initiator has varied in all of these cases. For instance, tributyltin alkoxides have been shown to initiate lactone polymerization via chain growth, and NMR analysis has been used to identify alkoxide chain end residues, thus indicating that these compounds provide the initiating species in addition to serving as catalysts in these polymerizations [7]. However, it has been shown that organotincarboxylates do not provide an initiating species, but catalyze the reactions of alcohols or water with the lactone ring [6]. In this case, carboxylate initiation would necessitate the formation of an energetically unfavorable anhydride that has not been identified in end group analysis. Weiji [10] observed that organotin catalysts are only active in the presence of water, and concluded that the actual catalyst is the organotin hydroxide. Pennings *et al*. [11] showed that in polymerizations of lactide involving stannous octoate, in the absence of any purposely added initiator, the molecular weight decreased as the amount of stannous octoate increased. They proposed that this was caused by the presence of water in the stannous octoate, and thus the more catalyst used, the more water that was introduced to the system. For cases in which a purposefully added initiator, for example an alcohol, has been used with stannous octoate in the polymerization of ε–caprolactone or *L,L*-lactide, there has been no spectroscopic evidence of chains that were initiated with water; rather, all chains appear to have been initiated with the alcohol [12, 13]. Essentially water initiation would produce carboxylic acid end groups in conjunction with hydroxyl end groups, and these carboxylic acids could condense with hydroxyl groups until their presence was undetectable by spectroscopic techniques. In fact, Pitt *et al*. [14] demonstrated the equivalent role of a water molecule and an alcoholic hydroxyl group as initiators in the stannous octoate catalyzed polymerization ε–caprolactone. However, whether or not water activates stannous octoate as readily as an alcohol has not been explored. The activation of stannous octoate has been extensively studied by Zhang and coworkers; [15] specifically, they investigated the effect of alcohols and carboxylic acids on lactide polymerization in the presence of stannous octoate. As expected, alcohols were shown to increase the rate of polymerization through activation of the catalyst; yet, carboxylic acids were shown to retard stannous octoate through deactivation. This deactivation of stannous octoate by carboxylic acids was also demonstrated by Weij [10].

This paper focuses on the role of water, introduced with stannous octoate, and stannous octoate in the ethylene glycol-initiated polymerization of ε–caprolactone. Experiments were conducted in which ε–caprolactone was polymerized using stannous octoate as catalyst, with and without ethylene glycol and with delayed addition of ethylene glycol. GPC and NMR analysis of the materials obtained form these experiments help better understand the effect that water and stannous octoate have on the structure, molecular weight, and molecular weight distribution of ethylene glycol-initiated poly(ε-caprolactone). Information gained from these experiments give insight into the mode of initiation and how it changes with catalyst concentration. Additional experiments were conducted in which water and 2-ethylhexanoic acid were added to anhydrous ethylene glycolinitiated polymerizations of ε-caprolactone. ^{1}H NMR spectroscopy was conducted on these systems to monitor percent conversion at various time intervals. Time conversion curves of these systems were used to compare their propagation rates. Matrix-assisted laser desorption/ionization time-of-flight mass spectroscopy [16-18] was conducted on these systems, and the results of the analysis were used to substantiate the conversion data analyses.

EXPERIMENTAL

Materials

2-Ethylhexanoic acid (EHA) was freshly distilled from stannous 2-ethylhexanoate, and tetrahydrofuran (THF) (Fisher) was freshly distilled fresh from calcium hydride. The following reagents were used without further purification: acetone (Fisher), chloroform-*d* (99.8 atom%, 1% TMS) (Aldrich), ε–caprolactone (CAP) (Union Carbide), 2,6-dihydroxybenzoic acid (Aldrich), ethylene glycol (anhydrous) (AEG) (Aldrich), ethylene glycol (EG) (Fisher), hexanes (Fisher), methylene chloride (Fisher), and stannous 2-ethylhexanoate (stannous octoate) (SO) (Sigma).

Characterization

Routine ^{13}C and ^{1}H NMR spectra were recorded on a Bruker AC-200 spectrometer using 5 mm o.d. tubes, deuterated solvents, and tetramethylsilane (TMS) as an internal reference. Sample concentrations were 25% (w/v) for ^{13}C NMR and 5% (w/v) for ^{1}H NMR. 2-D ^{1}H-^{13}C shift-correlated NMR spectra were recorded on a AC-300 spectrometer with a sample concentrations of 50% (w/v).

Polymer samples were subjected to gel permeation chromatography (GPC) to determine number average molecular weights (M_n) and polydispersities, M_w/M_n (MWD), relative to polystyrene standards (Polysciences Corporation). A Waters GPC system was used, equipped with a Waters model 510 HPLC solvent delivery pump, a Waters model 410 differential refractometer detector operating at 30°C, an Alcott model 728 autosampler, a Valco injector, and two Polymer Laboratories gel μ–Mixed-D columns. Freshly distilled THF served as the mobile phase and was delivered at a flow rate of 1.0 mL/min. Sample concentrations were approximately 4 mg/mL in THF, and the injection volume was 100 μL.

Matrix-assisted laser desorption/ionization time-of-flight mass spectroscopy (MALDI-TOF MS) was used to determine absolute molecular weights and molecular weight distributions that were otherwise unresolvable by GPC. A PerSeptive Biosystems Voyage™ RP MALDI-TOF Biospectrometry™ Work-station was used to obtain the MALDI-TOF mass spectra. 2,5-Dihydroxybenzoic acid was used as a matrix, and the solvent was acetone. The polymer samples were prepared by dissolving 2,5-dihydroxybenzoic acid (20 ma) and polymer (2 ma) in acetone (1

TABLE 1. ε–Caprolactone Polymerizations Conducted at 120°C.

Samp #	[CAP]:[EG]:[SO]	[CAP] (mol/kg)*	[EG] (mol/kg)	[SO] (mol/kg)	Total Rxn Mass (g)	Rxn Time (h)
1	10 : 1 : 0.0014	8.30	0.83	0.0012	15.94	16
2	10 : 1 : 0.02	8.26	0.82	0.017	13.87	16
3	10 : 1 : 0.1	8.04	0.80	0.081	13.05	16
4	10 : 1 : 0.5	7.11	0.71	0.36	15.80	16
5	10 : 0 : 0.0014	8.76	----	0.0012	23.88	16
6	10 : 0 : 0.02	8.70	----	0.017	17.62	16
7	10 : 0 : 0.1	8.46	----	0.085	12.50	16
8	10 : 0 : 0.5	7.44	----	0.37	13.23	16
9	10 : 0 : 0.0014	8.76	----	0.0012	26.03	72

*mol of reagent per kg of total reaction mass
CAP = ε-caprolactone
EG = ethylene glycol
SO = stannous octoate

mL). The probe tips were loaded with the polymer/matrix solution in a range of 0.5-1.5 μL.,

Poly(ε–Caprolactone) Synthesis

Bulk polymerizations (15-20 g) were carried out at 120°C in 20 mL vacuum-sealed glass ampoules equipped with magnetic stirring. Ampoules were dried at 145-155°C for 24 hours and cooled under a flow of dry nitrogen. Table 1 lists molar ratios of monomer (CAP), initiator (EG), and catalyst (SO) used in the polymerizations of ε-caprolactone.

A representative experimental procedure was as follows (Sample 4): to an ampoule equipped with a heat-sealable restriction were added ε-caprolactone (12.82 g, 1.12 x 10^{-1} mole), ethylene glycol (0.70 g, 1.13 x 10^{-2} mole), and stannous octoate (2.27 g, 5.60 x 10^{-3} mole). The ampoule was placed on a vacuum line and subjected to three freeze-pump-thaw cycles prior to being heat-sealed with a torch. The sealed ampoule was placed in a 120°C oil bath for 16 hours with continuous magnetic stirring of the contents. The polymerization was quenched in an ice-water

TABLE 2. ε–Caprolactone Polymerizations Conducted at 120°C with Delayed Ethylene Glycol Additions

Samp #	**[CAP]:[EG]:[SO]**	**[CAP] (mol/ kg)***	**[EG] (mol/ kg)**	**[SO] (mol/ kg)**	**Total Rxn Mass (g)**	**(a) Time of EG Addn (h)**	**(b) Total Rxn Time (h)**
10	10 : 1 : 0.0014	8.31	0.82	0.0014	5.48	16	32
11	10 : 1 : 0.02	8.25	0.82	0.017	5.50	16	32
12	10 : 1 : 0.1	8.04	0.81	0.080	5.58	16	32
13	10 : 1 : 0.5	7.11	0.71	0.36	6.32	16	32

*mol of reagent per kg of total reaction mass
CAP = ε-caprolactone
EG = ethylene glycol
SO = stannous octoate

bath, the ampoule was broken open, and the contents were divided into two roughly equal portions. One portion provided a crude sample for GPC analysis. To the other was added methylene chloride (60 mL), and the resulting solution was precipitated into a ten-fold excess of stirred hexanes. The hexanes layer was decanted, and the polymer was washed with hexanes (2 x 100 mL). The polymer was then redissolved, transferred to a specimen jar, dried for 24 hours in a 60°C oven, and then for 24 hours in an 25°C *in vacuo.* NMR spectroscopy was carried out on polymer samples purified by precipitation.

Delayed Ethylene Glycol Addition in Poly(ε–Caprolactone) Synthesis

Bulk polymerizations (5-10 g) were carried out at 120°C in 30 mL test tubes equipped with magnetic stirring and 24/40 ground glass joints sealed with evacuated glass stoppers wrapped with teflon tape (these reactors are closed, not sealed). Table 2 lists molar ratios of monomer (CAP), initiator (EG), and catalyst (SO) used in the polymerizations. A representative experimental procedure was as follows (Sample 11): to a test tube were added ε–Caprolactone (5.18 g, 4.54 x 10^{-2} mole), and stannous octoate (0.037 g, 9.13 x 10^{-5} mole). The test tube was purged with nitrogen and heated in a 120°C constant temperature bath for 16 hours with continuous stirring. An aliquot was removed, and ethylene glycol (0.28 g, 4.51 x

TABLE 3. Model Compound Syntheses Conducted at 120°C for 16 hours.

Samp #	[CAP]:[EG]:[SO]	[CAP] (mol/kg)*	[EG] (mol/kg)	[SO] (mol/kg)	Total Rxn Mass (g)
14	0 : 2 : 1	----	3.78	1.89	9.08
15	4 : 2 : 1	4.06	2.03	1.01	8.18

*mol of reagent per kg of total reaction mass
CAP = ε-caprolactone
EG = ethylene glycol
SO = stannous octoate

10^{-3} mole) was added to the test tube. The polymerization was then carried out for an additional 16 hours with continuous stirring.

Model Compound Synthesis

Glassware was dried at 145-155°C for 24 hours) and cooled under a flow of dry nitrogen. Reactions (1-10 g) were carried out at 120°C in 30 mL test tubes equipped with magnetic stirring and 24/40 ground glass joints sealed with evacuated glass stoppers wrapped with seflon tape (these reactors are closed not sealed). Table 3 lists molar ratios of monomer (CAP), initiator (EG), and catalyst (SO) used in the model compound reactions. A representative experimental procedure was as follows (Sample 15): to a test tube were added ε-caprolactone (3.79 g, 3.32 x 10^{-2} mole), ethylene glycol (1.03 g, 1.66 x 10^{-2} mole), and stannous octoate (3.36 g, 8.29 x 10^{-3} mole). The test tube was purged with nitrogen and heated in a 120°C constant temperature bath for 16 hours with continuous stirring. The reactions involving monomer were dissolved in methylene chloride and precipitated in a ten-fold excess of stirred hexanes. The hexanes layer was decanted, and the oligomer was rinsed with fresh aliquots of hexanes (2 x 100 mL). The isolated oligomer was then redissolved in methylene chloride, transferred to a specimen jar, dried for 24 hours in an 60°C oven, and then for 24-48 hours at 25°C *in vacuo*.

For reactions not involving monomer (Sample 14) a representative experimental procedure was as follows: to a test tube were added ethylene glycol (2.13 g, 3.43 x 10^{-2} mole) and stannous octoate (6.95 g, 1.72 x 10^{-2} mole). The test tube was purged with nitrogen and heated in a 120°C constant temperature bath; for 16 hours

TABLE 4. Kinetic Study for ε–Caprolactone Polymerizations Conducted at 80°C.

Samp #	[CAP]:[AEG]:[H_2O]: [EHA]:[SO]	[CAP] (mol/ kg)*	[AEG] (mol/ kg)	[H_2O] (mol/ kg)	[EHA] (mol/ kg)	[SO] (mol/ kg)	Total Rxn Mass (g)
16	40 : 1 : 0 : 0 : 0.0056	8.64	0.22	----	----	0.0012	20.94
17	40 : 1 : 0.5 : 0 : 0.0056	8.62	0.22	0.11	----	0.0012	20.93
18	40 : 1 : 1 : 0 : 0.0056	8.61	0.21	0.21	----	0.0012	21.10
19	40 : 1 : 2 : 0 : 0.0056	8.58	0.21	0.42	----	0.0012	21.29
20	40 : 1 : 0 : 0.025 : 0.0056	8.63	0.21	----	0.0053	0.0012	21.13
21	40 : 1 : 0 : 0.05 : 0.0056	8.63	0.21	----	0.011	0.0012	21.25
22	40 : 1 : 0 : 0.1 : 0.0056	8.61	0.22	----	0.021	0.0012	21.40

*mol of reagent per kg of total reaction mass
CAP = ε-caprolactone
AEG = anhydrous ethylene glycol
EHA = 2-ethylhexanoic acid
SO = stannous octoate

with continuous stirring. The resulting mixture contained a precipitate, and the supernatant was decanted. The supernatant was dissolved in methylene chloride, transferred to a specimen jar, dried for 24 hours in an 60°C oven, and then for 24-48 hours at 25°C *in vacuo.*

Kinetics of ε-Caprolactone Polymerization

Kinetics of polymerization were studied by taking aliquots from various polymerizations of ε–caprolactone; Table 4 lists the molar ratios of monomer (CAP), initiators, (AEG) and (H20), reagents (EHA), and catalyst (SO). A representative procedure was as follows (Sample 17): to a test tube were added ε-caprolactone (20.65 g, 1.81 x 10^{-1} mole), anhydrous ethylene glycol (0.28 g, 4.51 x 10^{-3} mole), and stannous octoate (0.01 g, 2.47 x 10^{-5} mole). The test tube was purged with nitrogen and heated with continuous stirring in a 80°C constant temperature bath for 8 hours, at which time the first aliquot was taken. Additional aliquots were taken at various time intervals, and the polymerization was stopped at 188 hours. A small sample of each aliquot was subjected to ^{1}H NMR analysis.

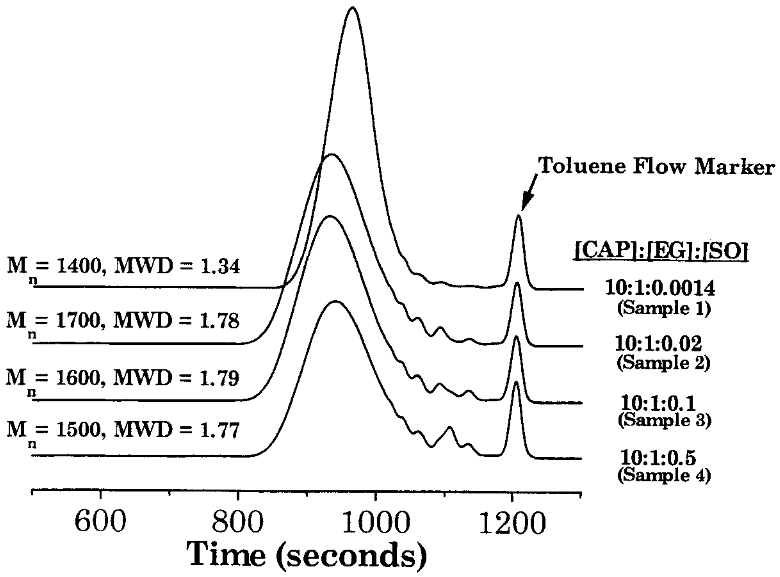

Figure 1. Gel permeation chromatograms of poly(ε-caprolactone)s resulting from ethylene glycol-initiated bulk polymerizations of ε-caprolactone at 120°C for 16 hours (Samples 1-4, Table 1).

RESULTS AND DISCUSSION

GPC Analysis of Polymerizations with Ethylene Glycol

ε-Caprolactone was polymerized at 120°C, with and without ethylene glycol as an initiator, using varying concentrations of stannous octoate as shown in Table 1. Figure 1 depicts GPC traces of the crude reaction products for Samples 1-4, all of which contained EG. In each case, the monomer conversion was essentially quantitative as evidenced by the complete absence of a peak eluting at 1177 seconds which can be observed when residual ε–caprolactone is present. It is significant that the number average molecular weights of the polymers, as determined by GPC analysis, remained virtually unchanged at full monomer conversion in spite of the broad range of catalyst concentration used; although, the molecular weight distribution (MWD) was significantly narrower at the lowest [SO]. Thus, the overriding determinant of molecular weight at this temperature is the CAP/EG ratio, rather than the level of SO catalyst or adventitious initiators such as water that might be carried into the reactor *via* the catalyst.

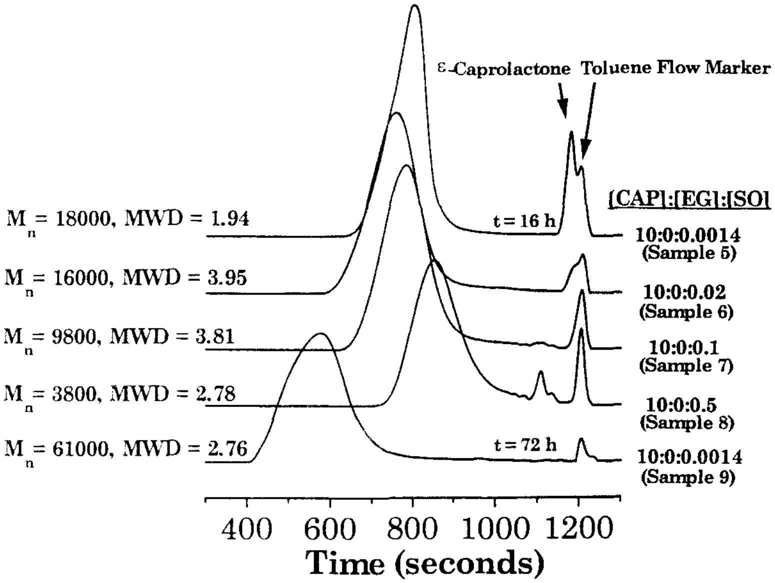

Figure 2. Gel permeation chromatograms of poly(ε-caprolactone)s resulting from water-initiated bulk polymerizations of ε-caprolactone at 120°C for 16 hours and 72 hours (Samples 5-9, Table 1).

GPC Analysis of Polymerizations Without Ethylene Glycol

Figure 2 depicts the GPC traces of control polymerizations (crude reaction mixtures) conducted using the same SO concentrations as in Figure 1, but in the absence of EG. In these systems, it was expected that water, introduced with the SO, would serve as the initiator, and indeed molecular weight was observed to fall as [SO] was increased. Samples 7 and 8, with the higher [SO], reached full monomer conversion; whereas, Samples 5 and 6 did not. This reduced monomer consumption suggests slower polymerization rate with water initiation; this slower rate may be due to lower catalyst activity in the presence of water initiated chains, or simply to a lower concentration of growing chains. Sample 9 (Table 1) was run using the same polymerization recipe as Sample 5, but the time of reaction was extended to 72 hours to observe differences in conversion, molecular weight, and molecular weight distribution. It is evident that full conversion of CAP monomer was achieved at longer reaction time due to its absence in the GPC trace. The molecular weight of Sample 9 is greater than 3 times that of Sample 5. This increase cannot be attributed solely to the increase in monomer conversion, assuming a chain growth type mechanism in which the degree of polymerization is determined strictly by the monomer/initiator ratio. Rather, it indicates participation of condensation polymerization, whereby water-initiated chains, bearing a carboxylic acid head group and hydroxyl tail group, act as A-B monomers. In addition, the molecular weight distribution broadened considerably, from 1.94 to 2.76, with a suggestion of bimodality in the GPC trace. This provides further evidence that polymerization is proceeding through a mixed mechanism, including both ring-opening and condensation polymerization.

GPC Analysis of Polymerizations with Delayed Addition of Ethylene Glycol

Polymerization reactions were run in which the addition of EG to the reactor was delayed for 16 hours as listed in Table 2. It was expected that the final molecularweight would be governed by the [CAP]/[EG] ratio, regardless of the molecular weight of the initial water-initiated polymerization. If this assumption were proved correct, it would provide support for the contribution of a step growth mechanism whenever water creates a free carboxylic acid chain end. GPC analysis was performed on aliquots taken from the reactor just prior to EG addition and after 16 hours of reaction with EG. Figure 3(a) depicts GPC traces of the crude polymerization mixtures prior to EG addition (Samples 10a-13a); these traces are similar to the results obtained in Figure 2. Molecular weight decreased with increasing [SO], except for Sample 10a, which showed a considerable amount of unreacted monomer in its GPC trace; thus, its molecular weight was lower than expected due to incomplete monomer conversion.

At the end of 16 hours, the ε–Caprolactone polymerizations depicted in Figure 3(a.) were subjected to a charge of EG at a concentration of one mole EG/10 moles CAP, and were allowed to react for an additional 16 hours. Figure 3(b) depicts the GPC traces of the resulting crude reaction mixtures. Samples 11b-13b, as expected, showed molecular weights and molecular weight distributions similar to those of Figure 1. Furthermore, the GPC traces show no unreacted EG. This indicates that the EG became incorporated into the polymers by transesterification and condensation reactions, and that the original amount of water introduced into the reactor is irrelevant with regard to the final molecular weight, which is determined only by the [CAP]/[EG] ratio. Sample 10a contained a considerable amount of unreacted monomer at the time of EG addition, and at the end of 16 hours its GPC trace showed a significant fraction of low molecular weight oligomers that had not condensed or transesterified with the higher molecular weight fraction. The presence of these oligomers suggests that at low catalyst concentration the ring-opening

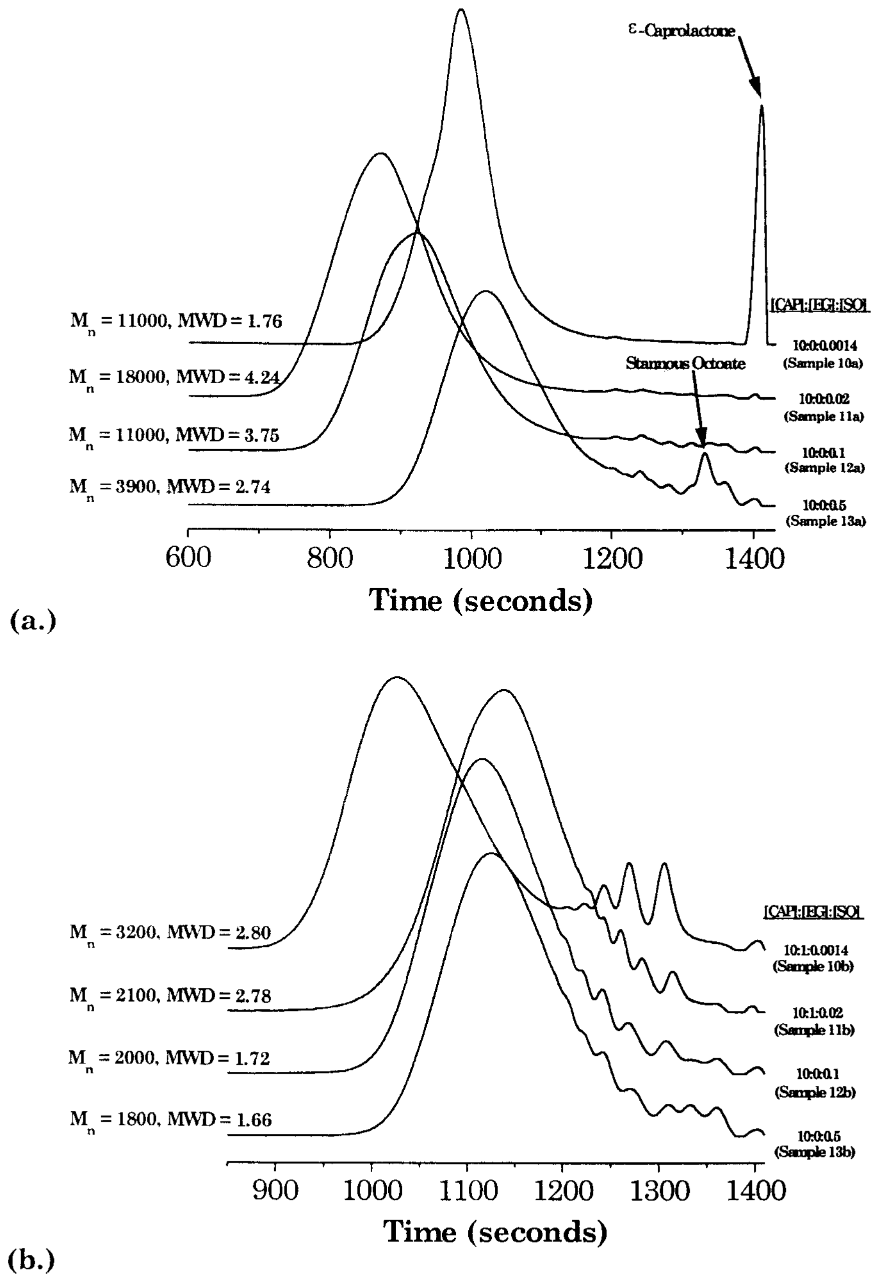

Figure 3. Gel permeation chromatograms of poly(ε-caprolactone)s resulting from (a) the reaction of stannous octoate with ε-caprolactone for 16 hours at 120 °C (Samples 10a-13a, Table 2), and (b) the reaction in which ethylene glycol was added to the samples in (a) and reacted for an additional 16 hours at 120°C (Samples 10b-13b, Table 2).

polymerization is much faster than transesterification and that, given sufficient time, Sample 10b would equilibrate into a monomodal distribution similar to those observed for samples 10b-13b.

NMR Structural Analysis of Polymers and Model Compounds

To determine whether SO was being incorporated in the polymers, either in the presence or absence of EG, the crude products from Samples 4 and 8 were precipitated to remove unbound SO, and ^{13}C NMR analysis was conducted to elucidate polymer structure. GPC analysis conducted on the samples before and after precipitation showed that precipitation was indeed successful in the removal of excess stannous octoate.

To facilitate subsequent discussion of the NMR spectra, the various possible structures present in these systems are depicted in Figure 4. Structures **P1-P7** are the possible structures resulting from polymerizations of CAP catalyzed by SO, in the presence and absence of EG, and **M1**, **M2**, and **M3** are the likely reaction products from the reaction of EG and SO in the absence of monomer. These structures are referred to in the spectroscopic analysis of polymers, Samples 4 and 8, and model systems, Samples 14 and 15, respectively.

Figure 5 depicts the ^{13}C NMR spectra of precipitated Samples 4 and 8. In Sample 8, produced without EG, extremely high concentrations of SO relative to CAP produced a polymer structure consisting of a carboxylic acid group at one end of the chain (water initiation) (**P5**) and a mixture of hydroxyl (**P7**) and 2-ethylhexanoate (2-EH) ester groups (**P6**) at the other end. The peaks marked 2-EH in the NMR spectrum were attributed to the 2-ethylhexanoate moieties of **P6** end groups. The carbonyl carbon of the carboxylic acid group is visible at 176.3 ppm (c), and the main-chain carbonyl carbons appear at 173.4 ppm (a); the carbon adjacent, to the ultimate oxygen atom appears at 62.2 ppm (ε') for the hydroxyl end group and, at 63.6 ppm; (ε") when the hydroxyl group has esterified with 2-ethyl-hexanoic acid. 2-Ethylhexanoic acid may become available for condensation with the chain end through the equilibrium hydrolysis/alcoholysis of SO (Figure 6) [11, 15]. The fact that the ε" peak at 63.6 ppm is present provides strong evidence that the 2-ethylhexanoate moieties are bound to the polymer chain and not simply occluded. Furthermore, simple comparison of signal heights suggests that a large number of the hydroxyl end groups are esterified.

In Sample 4, produced with EG, a significantly different polymer structure was found. Compared to Sample 8, the number average molecular weight was 2.5 times lower, and thus the end group resonances were generally more prominent. It

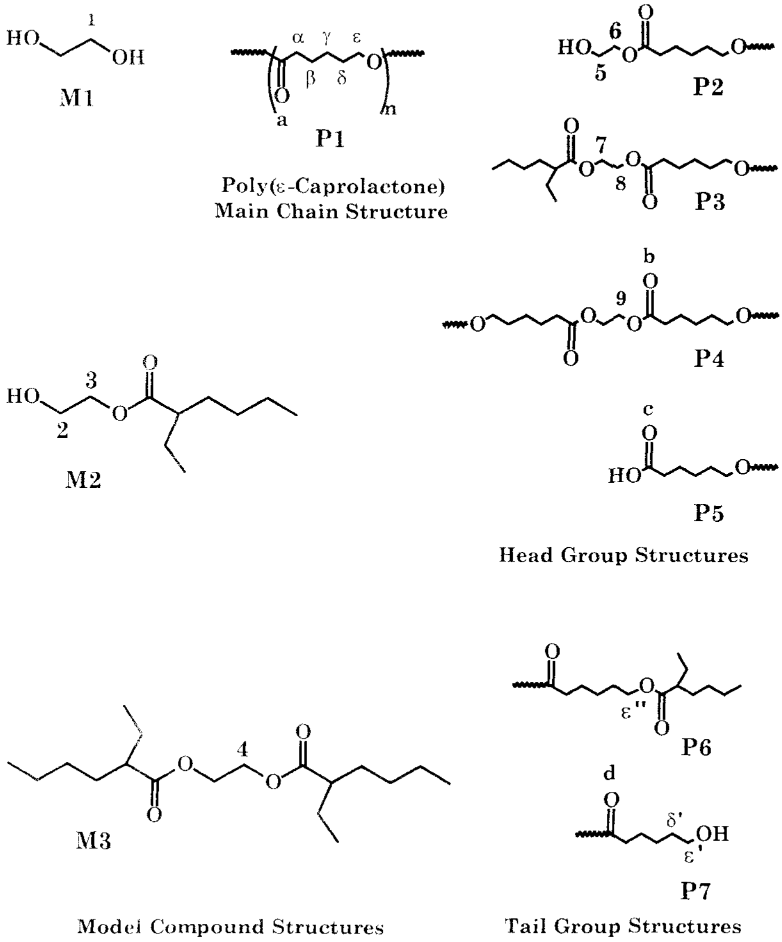

Figure 4. Various structures present from the reaction of ethylene glycol with stannous octoate, and from the ethylene glycol - and water-initiated polymerization of ε-caprolactone.

is significant that there were no visible carboxylic acid end groups, and most of the hydroxyl end groups remained unesterified. In fact, Sample 4 showed the carbon resonances characteristic of EG-initiated poly(ε-caprolactone) produced using more typical SO levels [12]; however, some 2-ethylhexanoate ester end groups were visible, as evidenced by the signal at 63.6 ppm (ε"). Interestingly, the spectrum showed evidence of a statistically unexpected preponderance of chains that were initiated by EG, one hydroxyl group of which remained unesterified (**P2**). On the basis of model compound studies, the signals at 60.8 ppm (6) and 65.8 ppm (5) were attributed to the methylene carbons of EG units of **P2** end groups.

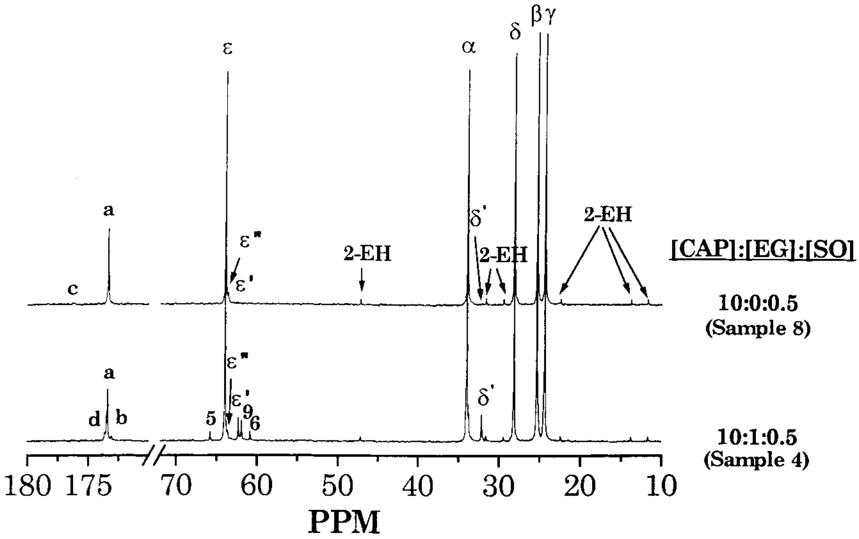

Figure 5. ^{13}C NMR spectra of ethylene glycol- and water-initiated poly(ε-caprolactone) (Samples 4 and 8, Table 1).

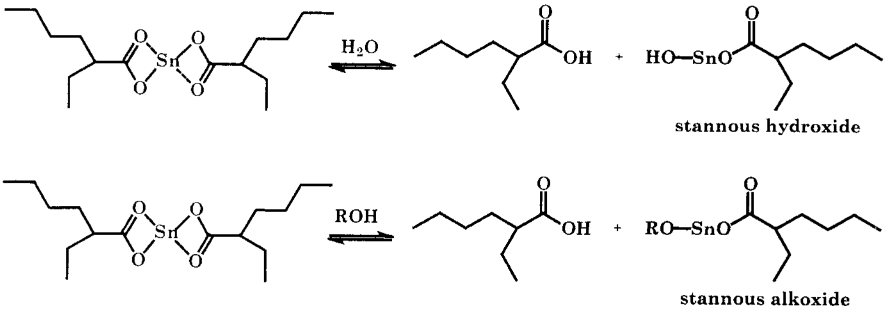

Figure 6. Hydrolysis/alcoholysis equilibrium reaction of stannous octoate.

To verify the assignments made in Figure 5, three model compounds were made (Samples 14 and 15, Table 3). Sample 14 was formed from the reaction of EG and SO in a molar ratio of 2:1. Sample 15 was formed by the reaction of CAP, EG, and SO in a ratio of 4:2:1, respectively.

Figure 7 depicts the oxymethylene region of the ^{13}C NMR spectra for Samples 4, 14, and 15. The spectrum of Sample 14, resulting from the reaction of EG with SO in the absence of CAP, was expected to produce three possible species (**M1**, **M2**, and **M3**). Since EG was in excess, a predominant signal was observed at 63.4 ppm (1) that belongs to the methylene carbons of unreacted EG (**M1**). Two

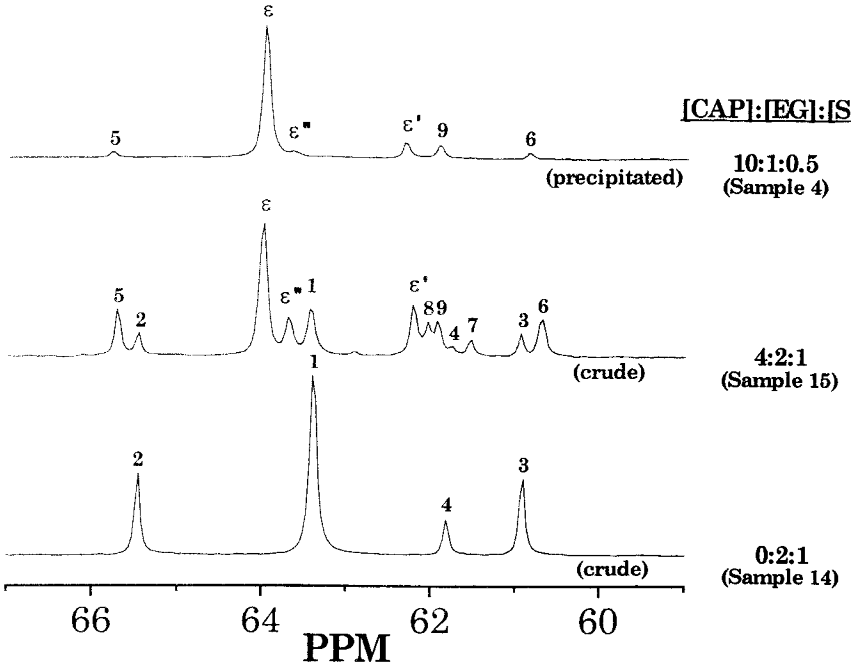

Figure 7. ^{13}C NMR spectra of the products of the reaction of ethylene glycol with stannous octoate, and the ethylene glycol-initiated oligomerization of ε-caprolactone (Sample 4, Table 1; Samples 14 and 15, Table 3).

signals at 65.5 ppm (2) and 60.9 ppm (3) of nearly identical intensities were attributed to the methylene carbons of an EG molecule that has reacted with one molecule of 2-ethylhexanoic acid (**M2**). The methylene carbon adjacent to the hydroxyl group was assigned to the downfield signal at 65.5 ppm (2), and the methylene carbon adjacent to the 2-ethylhexanoate moiety was assigned to the upfield signal at 60.9 ppm (3). Lastly, the signal at 61.8 ppm (4) was attributed to the methylene carbons of an EG molecule that has reacted with two EHA molecules (**M3**). The relative intensities of the four signals are consistent with the stoichiometry of the reaction.

Quantitative information concerning the composition of Sample 14 was obtained from integration of its ^{1}H NMR spectrum, shown in Figure 8. The results showed the sample to be composed of 57 mole % EG (**M1**), 36% compound **M2**, and 7% compound **M3**. 2-D ^{1}H-^{13}C shift-correlated NMR experiments (data not shown) confirmed the ^{1}H and ^{13}C NMR assignments made for this model compound.

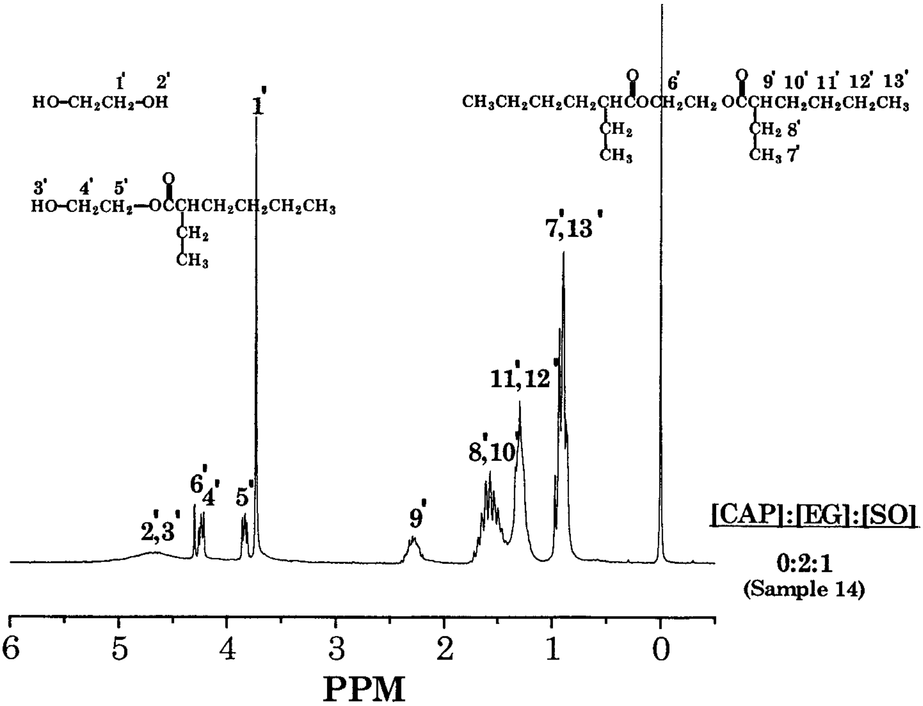

Figure 8. ^{1}H NMR spectrum of the products of the reaction of ethylene glycol with stannous octoate (Sample 14, Table 3).

Referring back to Figure 7, it is clear that the three species **M1**, **M2**, and **M3** are also present in the spectrum for Sample 15, which is the product of the reaction of CAP, EG, and SO in a ratio of 4:2:1. Their presence is not surprising in view of the low [CAP]/[EG] ratio and high catalyst level in the reaction. Upon precipitation of Sample 15 into hexanes, the signals for **M1**, **M2**, and **M3** (1, 2, 3, and 4) disappear in its NMR spectrum (not shown), and thus precipitation is effective in separation of these compounds from the oligomers of ε-caprolactone (**P1**, **P2**, **P3**, **P4**, **P6**, and **P7**).

Assignments for the resonances due to CAP oligomers, **P1**, **P2**, **P3**, **P4**, **P6**, and **P7**, in Sample 15 (Figure 7) were made in the following manner. The signal at64.0 ppm (ε) is characteristic of the 6-methylene carbon of non-terminal poly(ε-caprolactone) repeat units. Its presence suggests that polymerization of CAP didoccur to some extent, and presumably all oligomers containing two or more CAP units contribute to the intensity of this signal. The signal at 62.2 ppm, (ε'), is typical of ε-methylene carbons of terminal repeat units, i.e., those adjacent to hydroxyl end groups. All hydroxyl chain ends, other than those esterified with a 2 ethylhexanoate unit, contribute to this signal. The signal at 63.7 ppm, (ε) was assigned to the ε-methylene carbon adjacent to a 2-ethylhexanoate moiety as shown in compound **P6**. Two signals at 65.7 ppm (5) and 60.7 ppm (6) that have nearly identical intensities were assigned to the methylene carbons of an EG molecule that exhibited monofunctional initiation (**P2**). These assignments are supported by the fact that these same two resonances were observed in the spectrum of Sample 4. It is surprising in the case of Sample 4 that a significant fraction of EG units only initiated from one hydroxyl group to form compound **P2**, in spite of the greatly increased [CAP]/[EG] ratios. Structures of this type were not observed in Samples 1 and 2, when the [SO] was lower, and it is postulated that the large quantities of catalyst may serve to complex the EG molecules and hinder their ability to act as difunctional initiators. In the case in which one hydroxyl group of EG reacts with EHA and one hydroxyl group initiates the polymerization of CAP, compound **P3** is formed, and its methylene carbons exhibit different signals. The methylene carbon adjacent to the 2-ethylhexanoate moiety was assigned to the signal at 61.5 ppm (7), and the methylene carbon adjacent to the caprolactone moiety was assigned to the signal at 62.0 ppm (8). Support for these assignments comes from the fact that these signals are not present in the precipitated sample due to the high solubility in hexanes afforded by the 2-ethylhexanoate moiety. Lastly, EG units in which both hydroxyl groups successfully initiated CAP chains (**P4**) were assigned to the signal at 61.9 ppm (9), which is typical for EG-initiated poly(ε-caprolactone) [12].

Kinetic Investigation of Polvmerizations with Additions of Water and 2-Ethylhexanoic Acid

To better understand how the hydrolysis/alcoholysis equilibrium of SO affects SO activity, water and EHA were added to anhydrous ethylene glycol (AEG)-initiated polymerizations of CAP at 80°C. Monomer conversions were measured as a function of time using ^{1}H NMR spectroscopy, and time-conversion curves were used as a basis of comparison. The temperature was held at 80°C to suppress transesterification and condensation polymerization, and to eliminate water evaporation. Figure 9(a.) depicts percent conversion vs. time curves for AEG-initiated polymerizations containing 0, 0.5, 1.0, and 2.0 moles water/mole EG (Samples 16-19, Table 4). All of the polymerizations display an induction period lasting approximately 30-40 hours The data further show that water suppresses the propagation rate of the ring-opening polymerization of CAP. This rate suppression

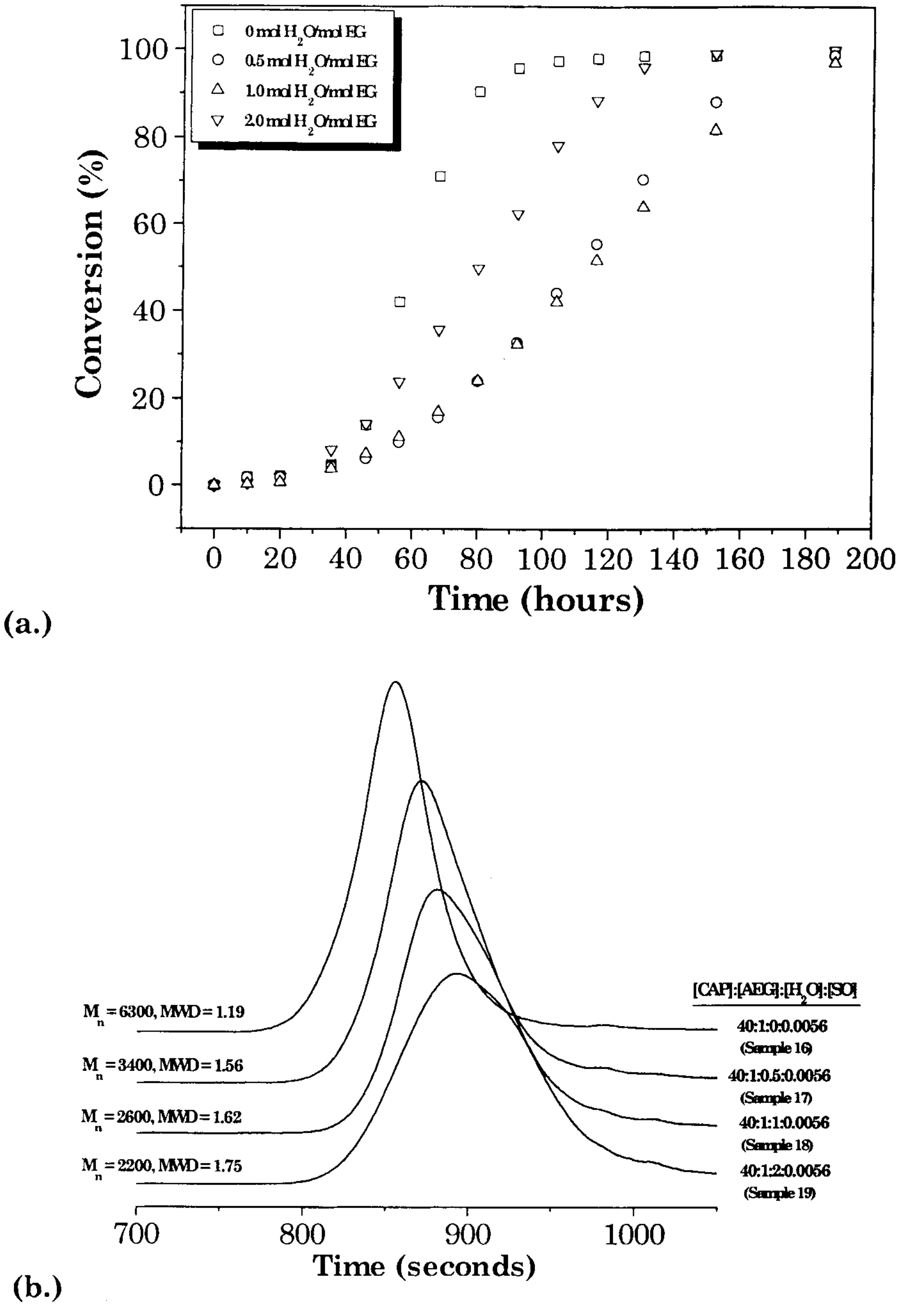

Figure 9. (a.) Conversion data for anhydrous ethylene glycol-initiated polymerizations of ε-caprolactone at 80°C in which 0, 0.5, 1, and 2 moles water/mole EG were added to the polymerizations, and (b.) gel permeation chromatograms of anhydrous ethylene glycol-initiated polymerizations of ε-caprolactone depicted in (a.) at 188 hours (Samples 16-19, Table 4).

probably results from the fact that water initiation creates carboxylic acid chain ends that displace the hydrolysis/alcoholysis equilibrium shown in Figure 6 away from the stannous hydroxide and alkoxide species, which are the active species responsible for propagation. However, when the concentration of added water was increased, the rate was observed to pass through a minimum (($[H_2O]$:[EG])~ 1) and then rise. This rise was attributed to the fact that water acts as an additional initiator in CAP polymerization at this temperature, yielding more total growing chains, both dormant and activated. Figure (9b) depicts the GPC traces of the polymers shown in the time-conversion curves, at nearly full conversion. The participation of water as an additional initiator is evidenced by the decrease in molecular weight and development of bimodality with increasing water content. At such a low polymerization temperature, the molecular weight is determined by the [CAP]/([EG] + $[H_20]$) ratio because the condensation of hydroxyl groups with carboxylic acid end groups produced from water initiation is suppressed.

Figure 10(a) depicts percent conversion vs. time curves for AEG- initiated polymerizations containing 0, 2.5×10^{-2}, 5.0×10^{-2}, and 1.0×10^{-1} mole EHA/mole EG (Sample 16 and Samples 20-22, Table 4). The data indicate that EHA suppresses the propagation rate of CAP, and similar to the polymerizations with added water, the rate passes through a minimum and then begins to rise as the amount of added EHA increases. However, the system containing the largest quantity of added EHA (1.0×10^{-1} mole) clearly produces a slower propagation rate than a system containing no added EHA. Figure l0(b) depicts the GPC traces of the polymers shown in the time-conversion curves, at nearly full conversion. They show that molecular weight remains fairly constant with increasing added EHA content; however, the molecular weight of the control sample is slightly higher than the molecular weights of samples with added EHA.

MALDI-TOF Mass Spectroscopic Analysis of Polymerizations with Added Water and 2-Ethylhexanoic Acid

MALDI-TOF MS was used to further analyze the final polymers from the kinetic study involving AEG-initiated polymerizations of CAP with and without water and EHA additions. Figure 11 depicts the MALDI-TOF mass spectrum of the AEG-initiated poly(ε-caprolactone) control (Sample 16, Table 4). The spectrum is a plot of intensity vs. mass/charge, and it consists of a number of equidistant peaks of varying intensity, each peak representing one oligomer in a mixture of oligomers. The peaks are symmetrical with respect to M_p (most probable molecular weight) and possess a Gaussian shape. The peak-to-peak mass/charge increment

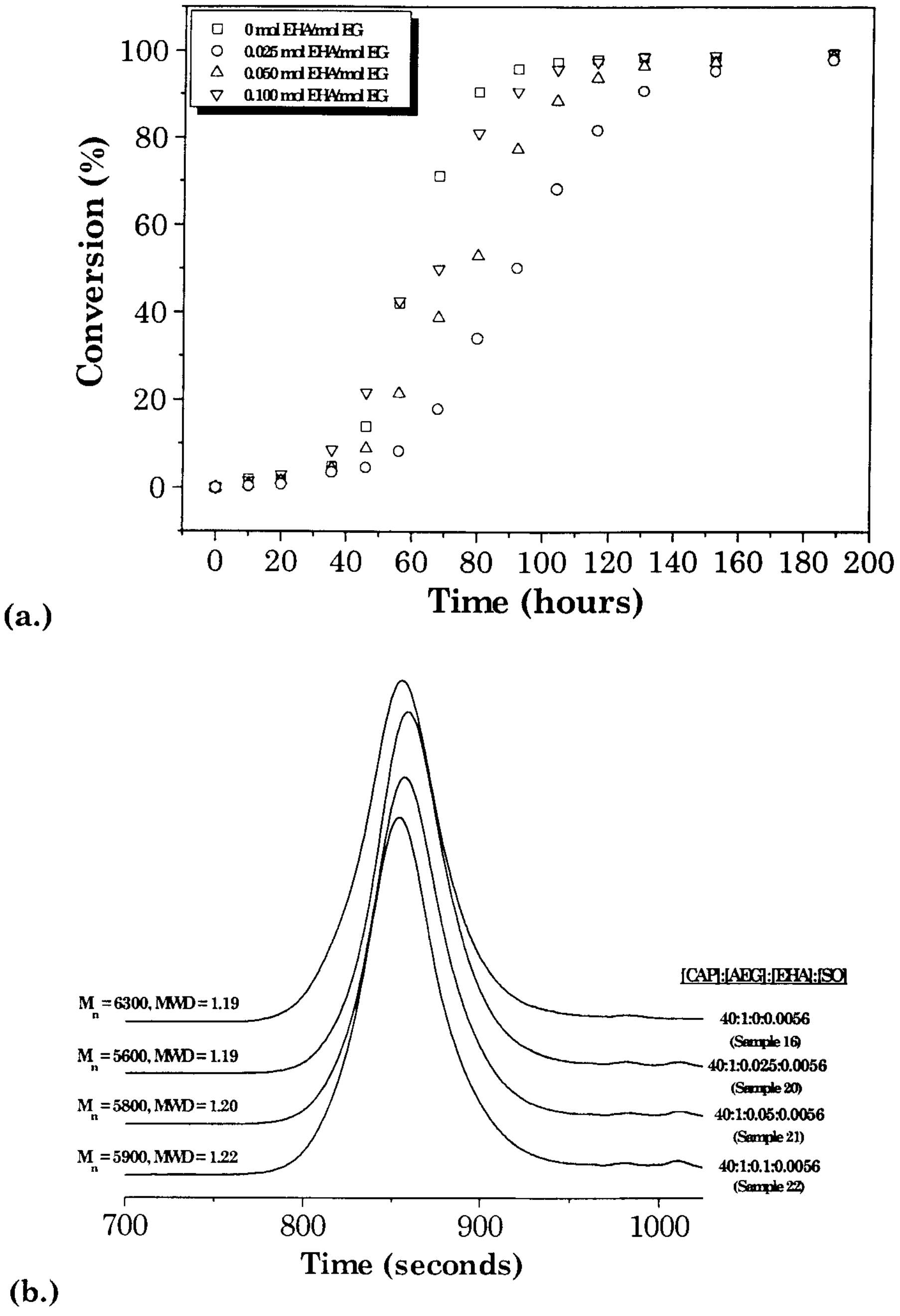

Figure 10. (a.) Conversion data for anhydrous ethylene glycol-initiated polymerizations of ε-caprolactone at 80°C in which 0, 0.025, 0.05, and 0.1 mole EHA/mole ethylene glycol were added to the polymerizations, and (b.) gel permeation chromatograms of anhydrous ethylene glycol-initiated polymerizations of ε-caprolactone depicted in (a.) at 188 hours (Samples 16 and 20-22, Table 4).

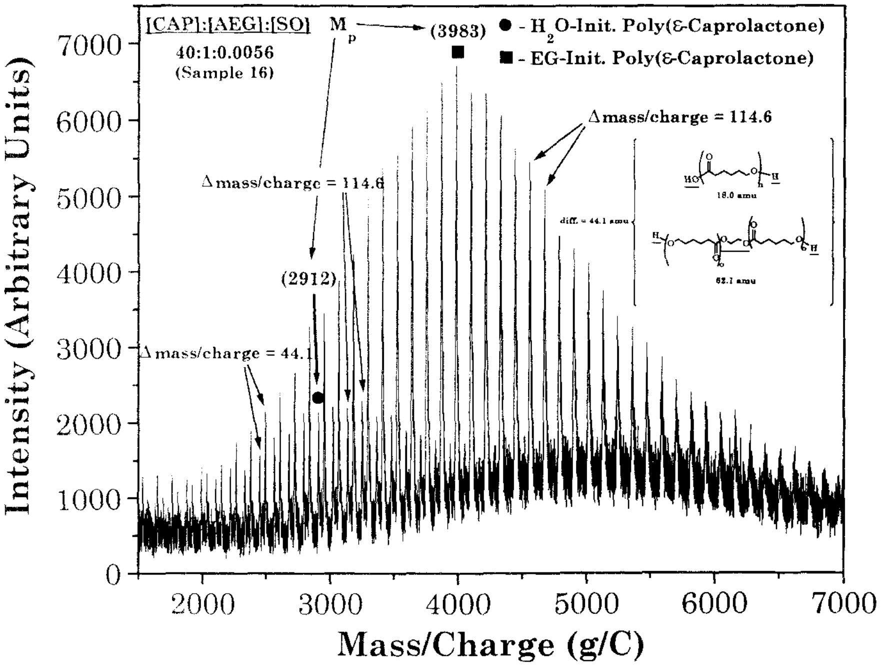

Figure 11. Matrix-assisted laser desorption/ionization time-of-flight mass spectrum of the anhydrous ethylene glycol-initiated polymerization of ccaprolactone at 80°C (control) (Sample 16, Table 4).

[Δ(mass/charge)] is 114.6 (approximately equal to the mass of the repeat unit in poly(ε-caprolactone) (114.14 g/mol)). The mass/charge of each peak corresponds to the mass of an oligomer and in the case of the ring-opening polymerization of CAP is theoretically equal to [(mass of initiator) + 114 (degree of polymerization)]. The MALDI-TOF mass spectrum shown in Figure 11 contains two distinct distributions, attributed to oligomers initiated from either water or EG. Therefore, in the case of the control polymer sample, the predominant oligomeric distribution was assigned to CAP initiated by EG (■), and the very low intensity MWD was attributed to CAP initiated by water (●). The compelling evidence for these assignments is a Δ(mass/charge) equal to 44.1, from one distribution to the other. This difference corresponds exactly to the difference in mass units between an EG moiety and a water moiety.

Figures 12(a), (b), and (c) depict the MALDI-TOF mass spectra for AEG initiated polymerizations containing 5.0 x 10^{-1}, 1.0, and 2.0 moles water/mole KG, respectively (Samples 17-19, Table 4). Each spectrum contains two distinct Gaussian distributions that were attributed to water: (●) and EG (■) initiation. As the amount of water added to each polymerization was increased, the overall molecular weight decreased and the water-initiated oligomers became a greater fraction of the whole. Regardless of the relative amounts of water vs. EG-initiated oligomers, the former remain a distinctly separate distribution with lower molecular weight. This lower molecular weight results from the fact that the EG-initiated oligomers are difunctional, and thus consist of two kinetic chains, whereas the water-initiated oligomers are only monofunctional.

Figures 13(a), (b), and (c) depict the MALDI-TOF mass spectra for AEG-initiated polymerizations containing 2.5 x 10^{-2}, 5.0 x 10^{-2}, and 1.0 x 10^{-1} mole EHA/mole AEG, respectively (Samples 20-22, Table 4). Similarly to the polymerizations containing added water, each spectrum contains two Gaussian distributions that were attributed to water (●) and EG (■) initiation. The M_p values for both the EG- and water-initiated distributions remained relatively constant with increasing [EHA]. However, it is clear that the water-initiated distribution for the control polymerization (Figure 11) has a higher M_p value (2912) than the M_p values for the water-initiated distributions in the EHA systems (Figures 13(a., (b), and (c)). These data suggest that water competes more effectively as an initiator in the EHA systems, but that the amount of water initiation does not change with increasing EHA.

CONCLUSIONS

^{13}C and ^{1}H NMR spectroscopies, GPC, and MALDI-TOF MS were used to probe the role of water and SO in the polymerization of CAP, with and without the presence of EG. For systems containing EG, GPC showed that [SO] has no significant effect on MW. In the absence of EG, water is the default initiator, and, between [SO] and MW. Water initiation is complicated by the fact that it produces primary chains that each contain one hydroxyl and one carboxylic acid end group. This allows for the possibility of condensation polymerization, and MW is neither predictable or stable in semi-open or open systems. Thus, both water and alcohols may serve as initiators of polymerization, i.e., either may open the ε-caprolactone ring to form a growing chain with an active hydroxyl end group, but the alcohol uniquely serves the additional role of MW modifier. This was neatly demonstrated by experiments in which EG was added to water-initiated polymerizations after

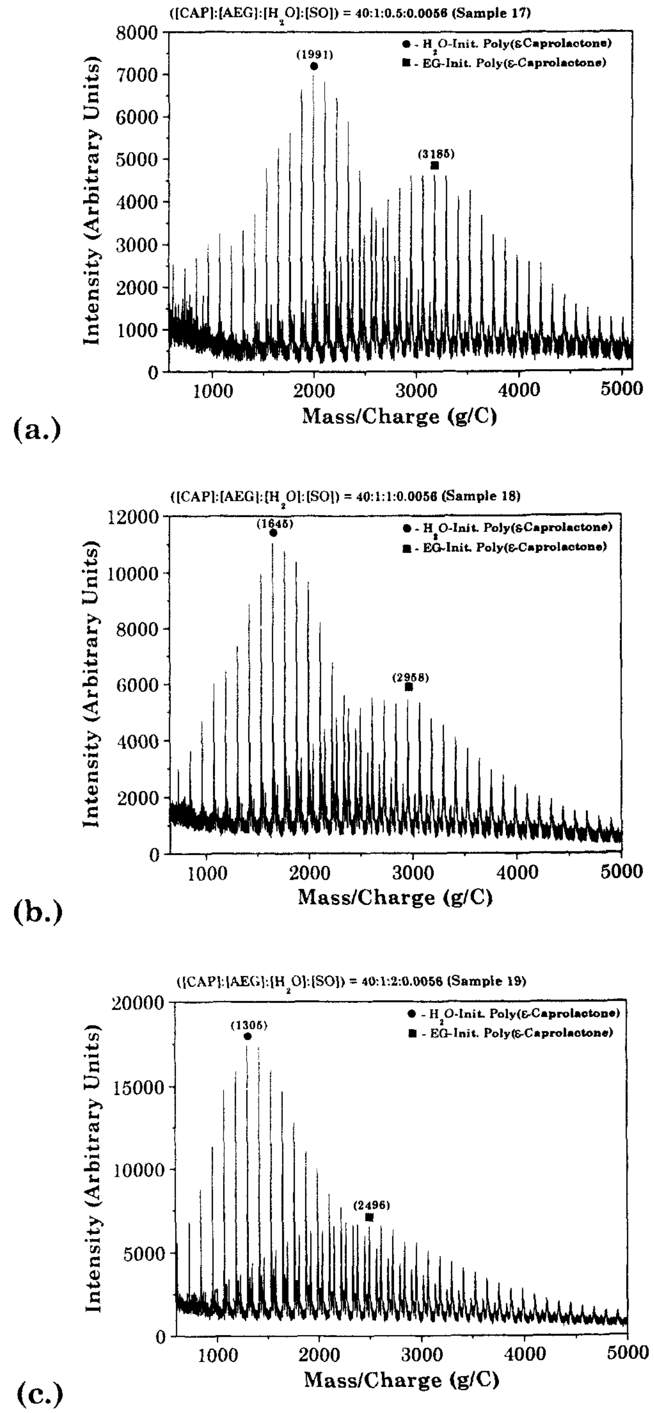

Figure 12. Matrix-assisted laser desorption/ionization time-of-flight mass spectra of anhydrous ethylene glycol-initiated polymerizations of ε-caprolactone at 80°C with the addition of (a.) 5.0 x 10^{-1} mole water/mole EG, (b.) 1.0 mole water/mole EG, and (c.) 2.0 moles water/mole EG (Samples 17-19, Table 4).

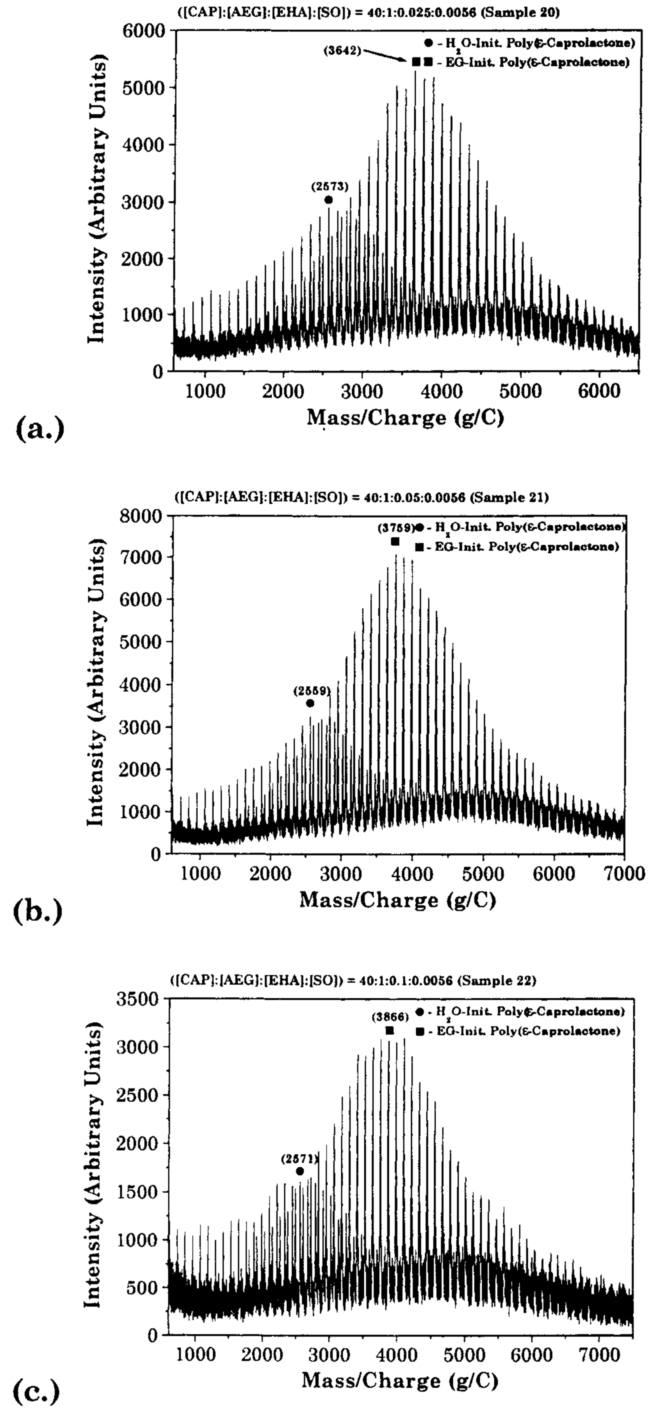

Figure 13. Matrix-assisted laser desorption/ionization time-of-flight mass spectra of anhydrous ethylene glycol-initiated polymerizations of ε-caprolactone at 80°C with the addition of (a.) 2.5 X 10^{-2} mole EHA/mole EG, (b.) 5.0 x 10^{-2} mole EHA/mole KG, and (c.) 1.0 x 10^{-1} mole EHA/mole EG (Samples 20-22, Table 4).

essentially complete monomer conversion. The newly added hydroxyl groups condense with the carboxylic acid chain ends and then, to the extent that they are in excess, undergo transesterification reactions until the final MW is reached, which **is** a function only of the [CAP]/[OH] ratio. Essentially the same molecular weight could be reached by adding the alcohol at the beginning.

Polymerizations run in the presence of EG were relatively unaffected by the use of atypically high SO concentrations. The MW distribution was broadened slightly, and surprisingly, the NMR spectrum showed a statistically improbable number of chains in which one of the hydroxyl groups of EG remained unesterified. A small fraction of hydroxyl end groups were observed to be ester)fied by EHA. In contrast, polymerizations run in the absence of EG produced chains that were almost wholly esterified by EHA.

Lower rates of polymerization were observed at 80°C when water was purposefully added to polymerizations initiated by anhydrous EG. MALDI-TOF MS showed that both EG and water were initiating chains and that the fraction of water-initiated chains increased with the amount of added water; thus an increasing fraction of the chains carried carboxylic acid group. The observed rate retardation likely represents yet another interaction of the carboxylic acid chain ends with the catalyst, that is, the hydrolysis/alcoholysis equilibrium shown in Figure 6 is perturbed by additional acid resulting in a reduction in the concenation of polymerization-active stannous alkoxide. The effectiveness of water in competing with the alcohol is apparently enhanced by the lower polymerization temperature. Addition of a low concentration of EHA to anhydrous EG-initiated polymerizations at 80°C also caused rate retardation. This could also be interpreted in terms of perturbing the hydrolysis/alcoholysis equilibrium away from polymerization-active stannous alkoxide. However, with increasing concentration of added EHA, the rate began to recover and MALDI-TOF MS showed that the fraction of water-initiated chains did not increase. These observations suggest that the effect of EHA is complex, and further study will be necessary for full elucidation.

In practical terms, even though excessively large concentrations of SO did have a minor effect on the end group structure of alcohol-initiated poly(ε-caprolactone), SO in catalytic amounts is an effective polymerization catalyst, and at reasonable concentrations does not alter the structure of the end groups to any extent detectable by NMR spectroscopy Furthermore, at typical polymerization temperatures, e.g., 120°C, its precise concentration has little or no effect on MW regardless of the amount of water that might be present in the catalyst.

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