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Alkyne Functional Block Copolymers as Precursors to Cobalt Nanoparticles

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Abstract of the Thesis

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Block copolymers are those that contain two or more homopolymer units connected together on a single chain. They are of great interest for their ability to phase-separate and form highly ordered structures on the nanometer scale. Amphiphilic block copolymers contain hydrophobic and hydrophilic blocks which allow them to self-assemble in aqueous solution, which has potential for various medical applications. Functionalized block copolymers also have potential to form metal-polymer hybrid materials that can self-assemble and form highly-ordered nanostructures, which may be useful for technological applications. In this work, alkyne-functional block copolymers were synthesized and used to create cobalt-copolymer composites.

ABA triblock copolymer poly[4-(phenylethynyl)styrene]-*b*-poly(ethylene oxide)-*b*-poly[4-(phenylethynyl)styrene] was synthesized at a variety of molecular weights by atom transfer radical polymerization (ATRP) of 4-PES onto a difunctional poly(ethylene oxide) macroinitiator (PEO, M_n=~10,000 g/mol). AB diblock copolymers poly(ethylene oxide)-*b*-poly[4-

(phenylethynyl)styrene] and polystyrene-*b*-poly[4-(phenylethynyl)styrene] were synthesized at a variety of molecular weights by ATRP of 4-PES onto monofunctional PEO and polystyrene (PS) macroinitiators (PEO M_n=~5,000 g/mol; PS M_n=~4400 g/mol). Copolymer products were analyzed by ^{1}H NMR spectroscopy and gel permeation chromatography (GPC). Polydispersities of diblock copolymers were fairly narrow (1.10-1.25), indicating well controlled polymerizations.   Copolymer samples were treated with $Co_2(CO)_8$ in solution to form cobalt-functional block copolymers. Transmission electron microscopy was used to investigate the structural properties of the cobalt composite of triblock copolymer $PPES_{55}$-PEO_{227}-$PPES_{55}$, and showed spherical structures 15-40 nm in diameter.

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List of Abbreviations

ATRP – Atom transfer radical polymerization

^{1}H NMR – Proton nuclear magnetic resonance

GPC – Gel permeation chromatography

TEM – Transmission electron microscopy

SAXS – Small angle x-ray scattering

PEO – Poly(ethylene oxide)

MPEO – Poly(ethylene oxide) monomethyl ether

PS – Polystyrene

4-PES – 4-(Phenylethynyl)styrene

PPES – Poly[(phenylethynyl)styrene]

PMDETA – 1,1,4,7,7-Pentamethyldiethylenetriamine

Bipy – 2,2'-Bipyridine

Acknowledgements

Introduction

Amphiphlic Block Copolymers

Block copolymers are a promising type of polymeric material with useful properties, which stem from the differences between the blocks within a molecule. These differences allow block copolymers to phase separate on the nanometer scale to form various structures. The size and shape of these structures depends on the composition of the copolymer and the relative lengths of its blocks. Figure 1 shows common types of structures that arise from block copolymer phase separation, including spheres, cylinders, lamellae, and gyroids. Amphiphilic block copolymers are those with both hydrophilic and hydrophobic blocks. In aqueous solution, amphiphilic block copolymers can form micelles in which the hydrophobic blocks form the core and the hydrophilic blocks form a shell (Figure 2) that is able to interact with the aqueous surroundings. The ability for such polymers to form these structures is being looked into for medical applications, as it may be used to encapsulate drugs that are poorly water-soluble for controlled delivery,[1] or help increase the effectiveness of gene transfer into skeletal muscle.[2] Amphiphilic triblock copolymers are also capable of forming gels in water by micellar bridging and can contain upwards of 90% water by weight.[3] These types of gels can also be designed to be responsive to environmental stimuli such as temperature or pH, making them useful for potential biomedical applications.[4]
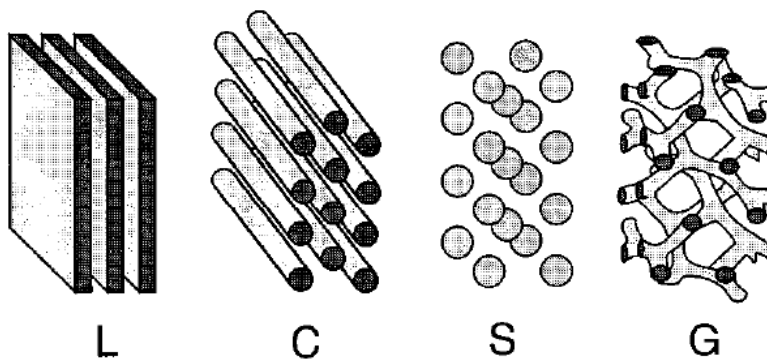
Figure 1: Lamellar, cylindrical, spherical, and gyroidal structures[5]

The goal of this research was to synthesize the amphiphilic A-B-A triblock copolymer poly[4-(phenylethynyl)styrene]-*b*-poly(ethylene oxide)-*b*-poly[4-(phenylethynyl)styrene] (PPES-*b*-PEO-*b*-PPES) and the A-B diblock copolymers poly(ethylene oxide)-*b*-poly[4-(phenylethynyl)styrene] (PEO-*b*-PPES) and polystyrene-*b*-poly[4-(phenylethynyl)styrene] (PS-*b*-PPES). These copolymers contain alkyne functionality in the 4-(phenylethynyl)styrene (PES) blocks, which may be used as ligands to form transition metal complexes. Self-assembly of copolymer-metal adducts can give rise to metal nanoparticles.[6] In this work, the use of cobalt to form such materials is being investigated due to its ability to complex to alkyne triple bonds and its potential to lead to magnetically active nanoparticles.[7] In order to form nanostructures with a narrow size distribution out of such block copolymers, precise control of the polymeric growth is required. Atom transfer radical polymerization (ATRP) was used to achieve such a goal and is discussed herein.
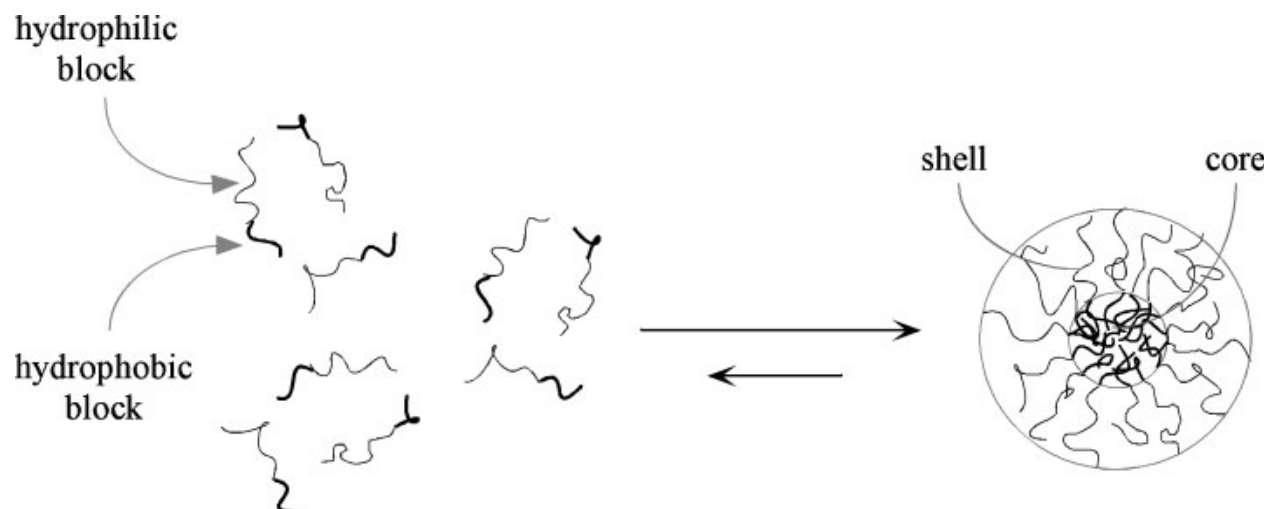
Figure 2: Amphiphilic block copolymers assembling into a spherical micelle.[1] The left side shows copolymer chains in a good solvent for both blocks, whereas assembly into the micelle on the right side would occur in aqueous solution.

Atom Transfer Radical Polymerization

Atom transfer radical polymerization (ATRP) is a metal-mediated living radical polymerization, which is initiated by a reversible single-electron redox process in which a halogen atom is transferred from a dormant initiator to the metal catalyst. A general scheme for ATRP is shown in Figure 3.
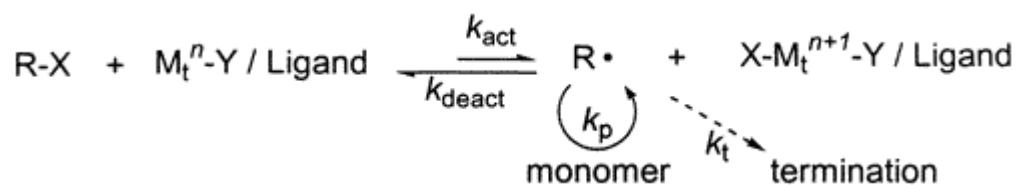
Figure 3: Transition metal-catalyzed ATRP [8]

The metal in complex M_t^n-Y/ligand undergoes a single-electron oxidation by the halogen X from the initiator R-X (k_{act}), leaving a radical species R• and the oxidized metal complex X- M_t^{n+1}-Y/ligand. The radical may then attack a monomer, forming a new carbon-carbon bond

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and generating a new radical (k_p), which then may attack another monomer molecule to propagate chain growth. Irreversible termination may occur when two radical species R• meet and react with one another, either by combination or disproportionation (k_t). Reversible deactivation occurs when R• reacts with the oxidized metal complex X- M_t^{n+1}-Y/ligand to return to a dormant state R-X (k_{deact}). Since deactivation is greatly favored in equilibrium for ATRP reactions, polymer chains can grow at much more even rates, resulting in narrow polydispersitites and well controlled reactions. The rate of polymerization depends on the equilibrium of activation $K_{eq} = \frac{K_{act}}{K_{deact}}$. This equilibrium must be precisely controlled because a low K_{eq} will produce very slow polymerization (or none at all) and a large K_{eq} will cause the concentrations of radical R• to be too high, resulting in a higher number of irreversible termination reactions and poor control over the polymerization.

Initiators used in ATRP reactions are generally alkyl halides (R-X), where chlorine, bromine, and iodine are all acceptable as X. A good initiator should also be capable of stabilizing the initial radical by resonance, such as those having aryl, carbonyl, or allyl groups on the α-carbon relative to the halide. In addition to small molecule ATRP initiators, macroinitiators are also widely used. Examples of macroinitiators derived from polyethylene oxide (PEO) are shown in Figure 4. These macroinitiators feature carbonyl groups located on α-carbons relative to alkyl bromides.

Figure 4: PEO10k difunctional macroinitiator (left) and MPEO5k monofunctional macroinitiator (right)

A good monomer to use in a radical polymerization should have the ability to stabilize the propagating radicals that drive the reaction. Common monomers for use in ATRP include styrenes, acrylates, and acrylamides.[8] The monomer that is being studied in this work is 4-(phenylethynyl)styrene (4-PES) (Figure 5). This molecule should be a good monomer for ATRP because of the conjugated π-system in the styrene ring, which can stabilize the propagating radical at the benzyl position. 4-PES also contains the alkyne functionality, which can be used to form transition metal complexes. Copolymers containing poly[4-(phenylethynyl)styrene] blocks can be treated with metals to form metal-functional polymers.[6]

Figure 5: 4-(phenylethynyl)styrene (4-PES), the monomer used for ATRP

According to Matyjaszewski and Xia,[8] a good transition metal catalyst for ATRP must meet four prerequisites. First of all, there must be a metal center that has two readily available oxidation states separated by one electron. Secondly, the metal must have some affinity towards

halogens (chlorine, iodine, or bromine). Thirdly, the coordination sphere around the metal center must be expandable upon oxidation so that the metal may selectively coordinate to a halogen. Lastly, the initial ligand (shown as "ligand" in Figure 3) on the metal center must strongly complex to that metal. For this work, copper (I) bromide is to be used for the catalyst with 2,2'-bipyridine (bipy) or 1,1,4,7,7-pentamethyldiethylenetriamine (PMDETA) being used as ligands. These combinations meet all of these conditions and have been used effectively for ATRP reactions of similar compounds.[9, 10]

Running ATRP is possible in bulk, in solution, or in a heterogeneous system. If done in solution, there are many solvents to choose from depending on what monomer is used. The solvent must be able to dissolve the reagents, products, and catalysts being used. There must also be a minimal amount of interaction between the solvent and the reagents or catalysts. For this work, ATRP will be done in solution using anisole as the solvent, due to its high boiling point (154 °C) and ability to dissolve all reaction components.

Increasing the temperature used for ATRP will increase the rate of polymerization as it increases the radical propagation rate constant and the atom transfer equilibrium constant. This will cause higher k_p/k_t ratios, giving better control over the polymerization. The drawback to using higher temperatures is that it may increase the frequency of side reactions such as chain transfers. Temperature must also be in a range such that decomposition will not occur among the reaction components. The reaction time must also be chosen carefully. As an ATRP progresses, the rate of monomer conversion will decrease due to a decrease in the monomer concentration. The rates of side reactions, however, generally do not depend on the concentration of monomer, so there will be no significant change to these rates. If monomer conversion nears completion, end group functionality may be lost without much increase in the polydispersity index.

Therefore, reaction time should be limited such that monomer conversion does not exceed 95%.[8]

Experimental

Materials

Poly(ethylene oxide) (10,000 g/mol, Alfa Aesar), 4-dimethylaminopyridine (99% Alfa Aesar), 2-bromoisobutyryl bromide (97%, Alfa Aesar), Poly(ethylene oxide) monomethyl ether (5,000 g/mol, Alfa Aesar), 2-bromopropionyl bromide (97%, Alfa Aesar), 4-bromobenzyl bromide (98+%, Alfa Aesar), triphenylphosphine (99%, Acros), copper (I) iodide (98%, Alfa Aesar), phenylacetylene (98+%, Alfa Aesar), bis(triphenylphosphine)palladium (II) chloride (98%, Acros), copper (I) bromide (98+%, Strem), 2,2'-bipyridine (Alfa Aesar), 1,1,4,7,7-pentamethyldiethylenetriamine (99+%, Acros), 1-(bromoethyl)benzene (97%, Acros), dicobalt octacaronyl (stabilized with 1-5% hexane, Strem), magnesium sulfate (anhydrous, J.T. Baker), alumina (basic, activated, 50-200μm, Acros), silica gel (40-63μm, Silicycle), sodium hydroxide (pellets, 98.7%, J.T. Baker), sodium chloride (99%, VWR), sodium bicarbonate (99.7%, Mallinckrodt), chloroform (99%, J.T. Baker), dichloromethane (99.8%, HPLC grade, EMD), hexanes (98.5%, HPLC grade, EMD), tetrahydrofuran (99.9%, EMD), diethyl ether (99.5%, Mallinckrodt), methanol (99.8%, VWR), dimethylformamide (99.9%, EMD), and formaldehyde (37% aqueous solution, J.T. Baker) were all used as received from the manufacturer. Anisole (99%, Alfa Aesar) and triethylamine (100%, J.T. Baker) were passed through basic alumina columns before use in water-sensitive reactions. Styrene (stabilized, 99.9%, Fisher) was passed

through a column of basic alumina to remove radical inhibitors before use. Hydrochloric acid (36.5-38.0%, J.T. Baker) was diluted from ~12M down to 2M before use. Toluene (99.5%, VWR) was purified by distillation over lithium aluminum hydride and stored under N_2.

Instrumentation

^{1}H NMR spectroscopy was carried out on a 300 MHz Varian Gemini 2300 spectrometer using $CDCl_3$ or CD_2Cl_2 as solvents. GPC was performed at ambient temperature using THF (HPLC grade, J.T. Baker) eluent at a flow rate of 1.0 mL/minute. The apparatus consisted of a K-501 pump (Knauer), a K-3800 Basic Autosampler (Marathon), two PLgel 5 μm Mixed-D columns (300 X 7.5 mm, rated for polymers between 200-400,000 g/mol, Polymer Laboratories), and a PL-ELS 1000 Evaporative Light Scattering Detector (Polymer Laboratories). A PL Datastream unit (Polymer Laboratories) was used to acquire data, which was analyzed based on narrow polydispersity polystyrene standards in the molecular weight range of 580-400,000 g/mol (EasiCal PS-2, Polymer Laboratories). TEM imaging was performed using an FEI Tecnai12 BioTwinG2 transmission electron microscope at 80 kV. Digital images were captured with an AMT XR-60 CCD Digital Camera System.

Synthesis of PEO10k Difunctional Macroinitiator[11]
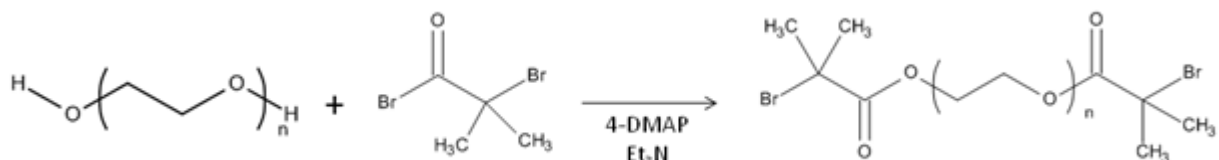

Figure 6: Synthesis of PEO10k macroinitiator

Poly(ethylene oxide) (12.33 g, 1.23 mmol, ~10,000 g/mol), 4-dimethylaminopyridine (32.2 mg, 0.263 mmol), and triethylamine (0.2757 g, 2.73 mmol) were dissolved in chloroform (35 mL) under N_2 and cooled in an ice bath. 2-Bromoisobutyryl bromide (1.054 g, 4.58 mmol) was dissolved in chloroform (~2 mL) and added to the mixture via syringe. The reaction mixture was allowed to warm to room temperature and left to stir for 2 days and then methanol (5 mL) was added to decompose any remaining bromoisobutyryl bromide. The mixture was washed with 75 mL of a 40:40:20 (by volume) mixture of water, saturated aqueous NaCl, and saturated aqueous $NaHCO_3$. The organic layer was extracted with chloroform (60 mL x3) and dried over $MgSO_4$. After filtration, the solvent was removed by rotary evaporation, producing a colorless solid. This product was stirred overnight in THF (100 mL) until fully dissolved. The product was precipitated into hexanes (1000 mL), filtered, and dried under vacuum for a week. ^{1}H NMR of the product showed traces of triethylamine, so the product was dissolved chloroform (60 mL) and washed with the water/NaCl/$NaHCO_3$ mixture again. It was then extracted, dried, and isolated by the same process as before to yield 9.45 g of white powder (75%). ^{1}H NMR (300 MHz, CDCl$_3$): δ 4.32 (t, 4H, J = 5.0 Hz), 3.4-3.9 (m, 4H per unit of PEO), 1.93 (s, 12H).
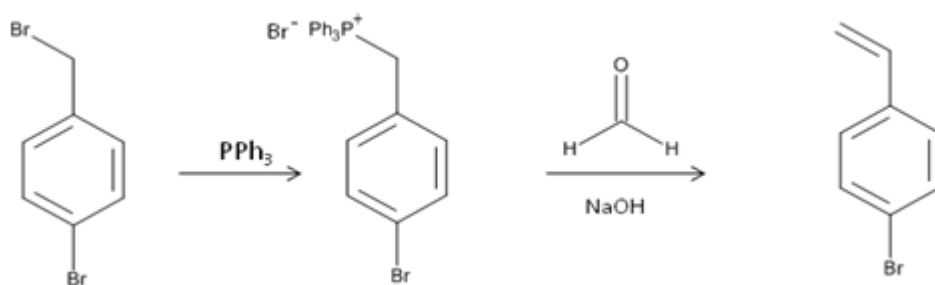
Synthesis of 4-(phenylethynyl)styrene[12]

Figure 7: Synthesis of 4-bromostyrene by Wittig reaction

Triphenylphosphine (25.23 g, 96.1 mmol) and 4-bromobenzyl bromide (26.11 g, 104 mmol) were dissolved in chloroform (125 mL) and stirred at 60 °C for 5 hours. The solvent was then removed using a rotary evaporator; the remaining solid was washed with diethyl ether and dried overnight. The resulting phosphonium bromide salt was added to NaOH (4.587 g, 115 mmol) and 300 mL formaldehyde (aqueous, 37%). This mixture was allowed to stir for 22.5 hours until no solid remained. The yellowish 4-bromostyrene layer was separated from the aqueous layer, which was then extracted with 300 mL of hexanes. The bromostyrene and hexanes layers were combined and the hexanes was evaporated off to yield ~20 g of yellowish liquid 4-bromostyrene (at this point the bromostyrene still contained some hexanes since 20 g would be >100% yield). ^{1}H NMR (300 MHz, CDCl$_3$): δ 7.25-7.50 (m, 4H), 6.6 (dd, 1H, J = 11.0 Hz, 17.7 Hz), 5.7 (d, 1H, J = 17.7 Hz), 5.3 (d, 1H, J = 11.0 Hz).
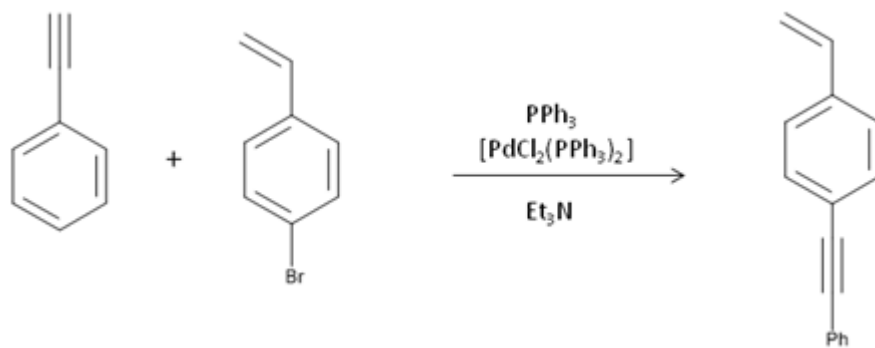
Figure 8: Synthesis of 4-(phenylethynyl)styrene by Sonogashira coupling

4-Bromostyrene (~20 g, ~110 mmol), triphenylphosphine (0.4525 g, 1.73 mmol), copper

(I) iodide (0.2343 g, 1.23 mmol), and phenylacetylene (15.3127 g, 150 mmol) were dissolved in

dry triethylamine (175 mL) and bubbled with N_2 for an hour.

Bis(triphenylphosphine)palladium(II) chloride (0.6341 g, 0.90 mmol) was added to the mixture,

which was then heated to 70 ^{0}C and left to stir for 69 hours under N_2. The reaction mixture was

filtered to remove the brown triethylammonium salt and the triethylamine was evaporated off.

The remaining solids were dissolved in hexanes and washed with a (1:1:1 by volume) mixture of

water, 2M HCl, and brine. The wash was extracted with hexanes and dried overnight with

anhydrous $MgSO_4$. After filtration to remove $MgSO_4$, the hexanes were removed on the rotary

evaporator. The mixture was passed through a large plug of silica and washed through with more

hexanes. The solvent was removed and the purified product was isolated by recrystallization

from a minimum amount of hexanes. 4-PES was isolated (3.49 g) as a slightly yellow crystalline

solid (15%). ^{1}H NMR (300 MHz, CDCl$_3$): δ 7.3-7.5 (m, 9H), 6.7 (dd, 1H, J = 11 Hz, 17.6 Hz),

5.7 (d, 1H, J = 17.6 Hz), 5.3 (d, 1H, J = 11 Hz).
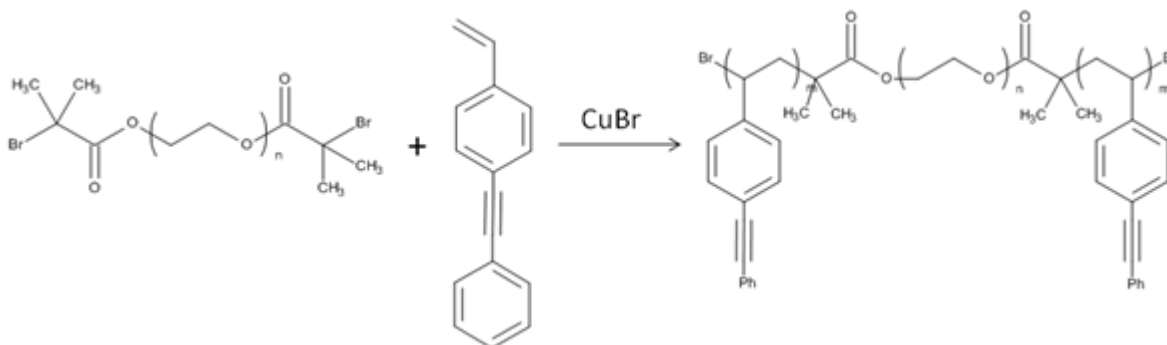
Typical Synthesis of PPES-b-PEO-b-PPES by ATRP[9]

Figure 9: Synthesis of triblock copolymer PPES-b-PEO-PPES by ATRP

PEO10k macroinitiator (0.5000 g, 0.049 mmol), 4-PES (0.3812 g, 1.87 mmol), and

PMDETA (0.0798 g, 0.46 mmol) were dissolved in anisole (5 mL) and added to a Schlenk tube.

The tube was degassed by two freeze-pump-thaw cycles, and then brought back up to room

temperature under N_2. The tube was opened, keeping N_2 outflow as to minimize re-entry of air,

and copper (I) bromide (0.0289 g, 0.20 mmol) was added. The mixture was then degassed by

two more freeze-pump-thaw cycles and sealed under N_2. It was then placed in an oil bath to stir

for 3 hours at 110 ^{0}C. The flask was then removed from the oil bath, opened to air, diluted in

chloroform and allowed to stir overnight to oxidize the copper. This was indicated by the change

in the color of the solution from a yellow-green to a deep emerald green upon oxidation of

copper. The oxidized solution was passed through a column of basic alumina (chloroform as

eluent) to remove the copper. The chloroform was evaporated off and the polymer was

precipitated from the remaining anisole into cold ether (100 mL). The solid was collected by

vacuum filtration (0.5892 g, ~75% yield based on conversion). ^{1}H NMR (300 MHz, CDCl$_3$): δ

6.4-7.6 (m, 9H per unit PPES), 3.4-3.9 (m, 4H per unit PEO), 0.8-2.2 (m, 3H per unit PPES).
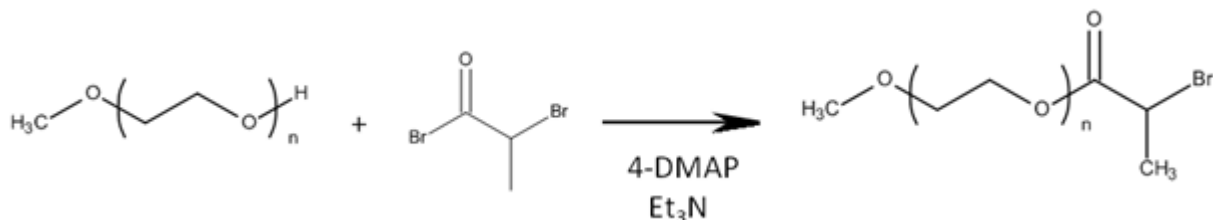
Synthesis of MPEO5k Monofunctional Macroinitiator[11]

Figure 10: Synthesis of MPEO5k macroinitiator by esterification

Polyethylene oxide monomethyl ether (10.0082 g, 2.0 mmol), 4-dimethylaminopyridine (21.3 mg, 0.17 mmol) and triethylamine (0.3248 g, 3.2 mmol) were dissolved in chloroform (60 mL) and bubbled with N_2 for 1 hour. The mixture was then placed in an ice bath to cool down to 0 °C. 2-Bromopropionyl bromide (0.7890 g, 3.65 mmol) was diluted in chloroform (~3 mL) and added slowly to the reaction mixture. The solution was allowed to warm up to room temperature and remained under active N_2 flow for an hour after removal of the ice bath. After stirring for 48 hours, the reaction was quenched by addition of methanol (5 mL). Workup procedure was identical to that used in synthesis of PEO10k macroinitiator. Precipitation into hexanes gave 8.92 g of white powder (87%). ^{1}H NMR (300 MHz, CDCl$_3$): δ 4.40 (q, 1H, J = 7.0 Hz), 4.32 (t, 2H, J = 4.5 Hz), 3.4-3.9 (m, 4H per unit of PEO), 3.38 (s, 3H), 1.82 (d, 3H, J = 6.9 Hz).

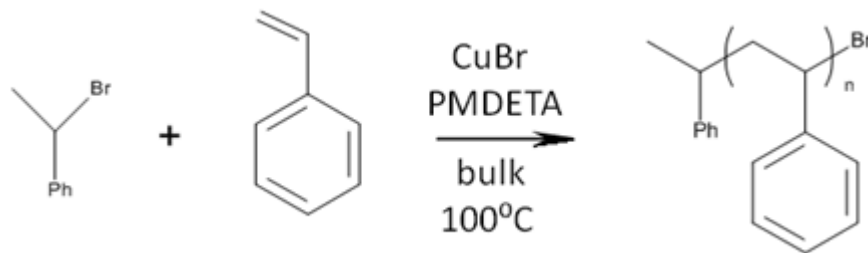<u>Synthesis of Polystyrene Macroinitiator</u>[13]

Figure 11: Synthesis of polystyrene macroinitiator by ATRP

Styrene was passed through a column of basic alumina to remove radical inhibitors. A

Schlenk tube was then charged with the styrene (4.5 mL, 39 mmol), 1-bromoethylbenzene (99

mg, 0.54 mmol), and PMDETA (58 mg, 0.34 mmol) and degassed by two freeze-pump-thaw

cycles. After two cycles, copper (I) bromide (36 mg, 0.25 mmol) was added to the mixture (with

active N_2 flow through the tube as to minimize air contamination) and the solution was subject to

two more freeze-pump-thaw cycles. It was then allowed to warm to room temperature, sealed

under N_2, and placed in an oil bath at 100 $^{\circ}$C for 16 hours. The resulting mixture was opened to

air, diluted with chloroform, and allowed to stir for several hours so that the copper could

oxidize. It was then passed through a column of alumina using chloroform as the eluent. The

solvent was removed using the rotary evaporator and the sample was precipitated from the

remaining styrene into methanol (100 mL). Vacuum filtration gave 2.57 g of a fine colorless

powder (72% yield based on conversion). Successful synthesis was determined by ^{1}H NMR and

GPC. ^{1}H NMR (300 MHz, CDCl$_3$): δ 6.3-7.2 (m, 5H per unit of PS), 0.8-2.2 (m, 3H per unit of

PS). GPC: M_n=7700, M_w/M_n=1.06.

Typical Synthesis of PEO-b-PPES by ATRP
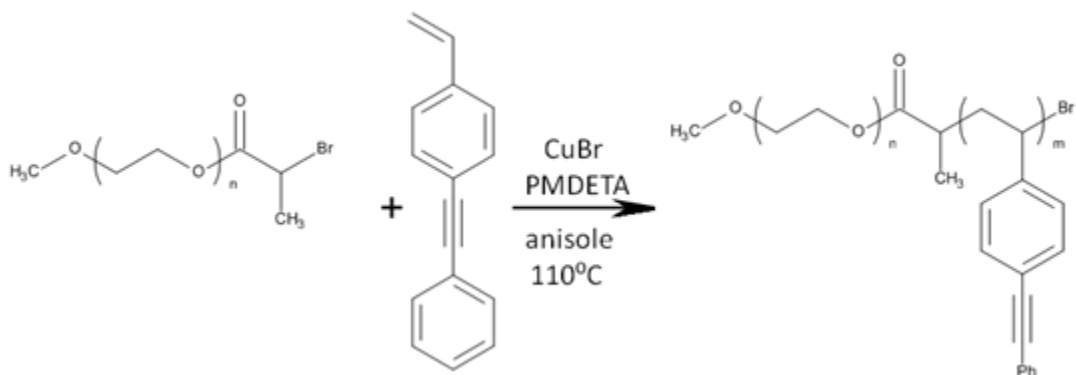
Figure 12: Synthesis of diblock copolymer PEO-b-PPES by ATRP

MPEO5k macroinitiator (0.249 g, 0.048 mmol), 4-PES (0.210 g, 1.03 mmol), CuBr (18 mg, 0.13 mmol), and PMDETA (40 mg, 0.23 mmol) were dissolved in anisole (2.6 mL) and heated at 110 °C under N_2 for 3 hours. Procedures for degassing and reaction workup are identical to ATRP procedures previously mentioned. Product was isolated by precipitation into cold hexanes from anisole. ^{1}H NMR (300 MHz, CDCl$_3$): δ 6.4-7.6 (m, 9H per unit PPES), 3.4-3.9 (m, 4H per unit PEO), 0.8-2.2 (m, 3H per unit PPES).

Typical Synthesis of PS-b-PPES by ATRP
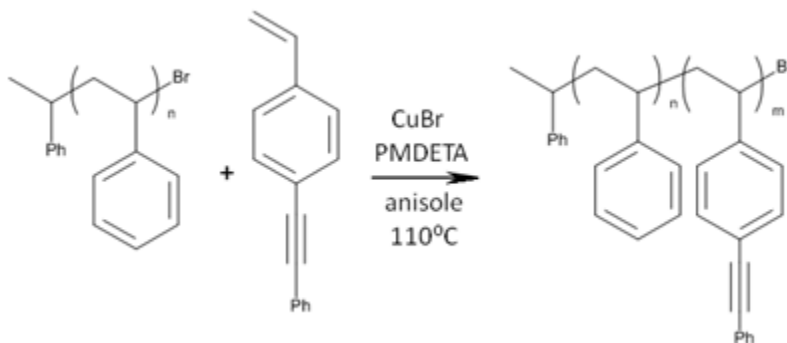
Figure 13: Synthesis of diblock copolymer PS-b-PPES by ATRP

Polystyrene macroinitiator PS2 (M_n = 4400 g/mol, 0.244 g, 0.055 mmol), 4-PES (0.252 g, 1.23 mmol), CuBr (15 mg, 0.11 mmol), and PMDETA (35 mg, 0.20 mmol) were dissolved in anisole (2.75 mL) and heated at 110 °C under N_2 for 5 hours. Procedures for degassing and reaction workup are identical to those previously mentioned. Product was isolated by precipitation into cold hexanes from anisole. ^{1}H NMR: δ 6.3-7.6 (m, 5H per unit of styrene and 9H per unit of 4-PES), δ 0.8-2.4 (m, 3H per unit of styrene and 3H per unit of 4-PES). GPC: M_n=7600, M_w/M_n=1.13.

Typical Procedures for the Addition of Cobalt Carbonyl to PPES Block Copolymers[14]
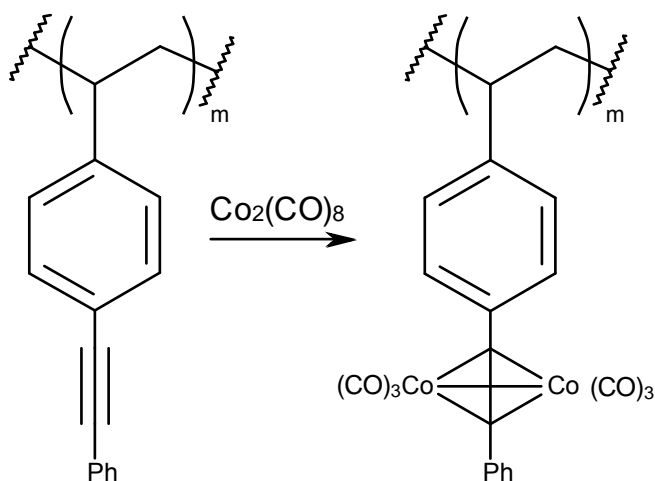
Figure 14: Formation of cobalt complexes on alkyne-functional PPES blocks

PPES-PEO-PPES:

A triblock copolymer sample (**A2**, $PPES_{55}$-PEO_{227}-$PPES_{55}$, 151mg, 0.005 mmol, 0.55 mmol of alkyne groups) was brought into a glovebox under a dry N_2 atmosphere. In the glovebox, an excess of dicobalt octacarbonyl (190 mg, 0.56 mmol) was weighed in a clean vial. The two samples were dissolved in 5 mL dry toluene each and mixed together. The dark brown solution was left to stir for 1 hour before being removed from the glovebox and precipitated into hexanes to give 187.5 mg of black powder (60% yield).

PEO-PPES and PS-PPES:

In a glovebox under a dry N_2 atmosphere, 108 mg of dicobalt octacarbonyl was weighed in a small vial. The vial was sealed with a rubber septum, brought out of the glovebox and placed under N_2. A diblock copolymer sample (**C8**, PEO_{113}-$PPES_{23}$, 99 mg, 0.01mmol) was

dissolved in 5 mL dry chloroform and injected into the $Co_2(CO)_8$-containing vial. The dark brown solution was allowed to stir for 1 hour before being opened to the atmosphere and precipitated into 100 mL cold hexanes. The precipitate was vacuum filtered to give 78 mg of brown powder (49%).

For PS-PPES diblock samples, the procedure was the same as described above, except precipitation was done in methanol.

TEM Sample Preparation[15]

Triblock copolymer sample (**A2**, $PPES_{55}$-PEO_{227}-$PPES_{55}$) was dissolved in a 1:1 (by volume) mixture of DMF and toluene at a concentration of ~5 mg/mL. Another sample (**A8**, $PPES_8$-PEO_{227}-$PPES_8$) was dissolved in toluene at 1.85 mg/mL. The solutions were then filtered through 0.45 μm PTFE filters and drop cast onto carbon-coated 300 mesh copper grids. The grids were allowed to air dry before examination. After initial TEM imaging, the grid containing the $PPES_{55}$-PEO_{227}-$PPES_{55}$ sample (**A2**) was heated in a vial at 100 °C under vacuum for 1 hour and imaged again by TEM.

Formation of Hydrogels from Triblock Copolymers[3]

50 mg of triblock copolymer samples were weighed out in clean vials. Each sample was dissolved in a minimal amount of dichloromethane and the vials were left open overnight to let the solvent evaporate off. 0.5 mL of water was added to each of the resulting copolymer films and allowed to sit for several hours.

Results and Discussion

Triblock copolymers

Successful synthesis of the PEO10k macroinitiator was confirmed by ^{1}H NMR spectroscopy. The spectrum for the PEO bromoester (Appendix, page 39) was consistent with the proposed structure. The appearance of a 4H triplet at 4.3 ppm was indicative of esterification; the signal represented the PEO CH$_2$ hydrogens adjacent to the ester functionality, which shifts the resonance downfield. A strong singlet at 1.9 ppm corresponds to the hydrogens on the two methyl groups on each end. Relative to the 4H triplet, the calculated area of this singlet is 10.83. Discrepancy between this calculated value and the expected value of 12 is likely due to instrument error.

A series of trials of ATRP were performed to synthesize triblock copolymers consisting of PPES-b-PEO-b-PPES. The earliest trials (labeled **A1**-**A8**) were conducted using 2,2'-bipyridine (bipy), a bidentate chelating agent, as the ligand for the catalyst complex. Bipy is often used in ATRP,[16, 17, 18] but it leads to slow polymerizations. PMDETA, a tridentate chelating agent, was used in later trials due to its significantly higher activation rate for CuBr complexes.[17] This reduced reaction times down from 20 hours (using bipy) to around 3 hours while still obtaining good control and conversion of monomer. The trial series **A1-A8** shows results for ATRP syntheses using the bipy catalyst system. These reactions were all run for 20 hours at 110 ^{o}C using various ratios of monomer to macroinitiator. ^{1}H NMR spectroscopy was used as the method for measuring the degree of polymerization that occurred in these reactions. Generally, gel permeation chromatography (GPC) is very useful for the measurement of polymer molecular weights and degree of polydispersity. GPC was not useful for the analysis of these

polymers, however, due to the use of polystyrene standards and the poor solubility of the triblock copolymers in THF. A better solvent for these polymers (such as DMF), along with the use of absolute molecular weight calculations (instead of using a standard) would likely be the best approach in GPC analysis. The ^{1}H NMR spectra of these triblock copolymers have three main points of interest: the PEO proton signal, the PPES aromatic proton signal, and the PPES alkyl proton signal. Comparison of the integrals of these three signals can give an approximation of the molecular weights of the PPES blocks. An example spectrum from a triblock copolymer sample is shown in Figure 15.

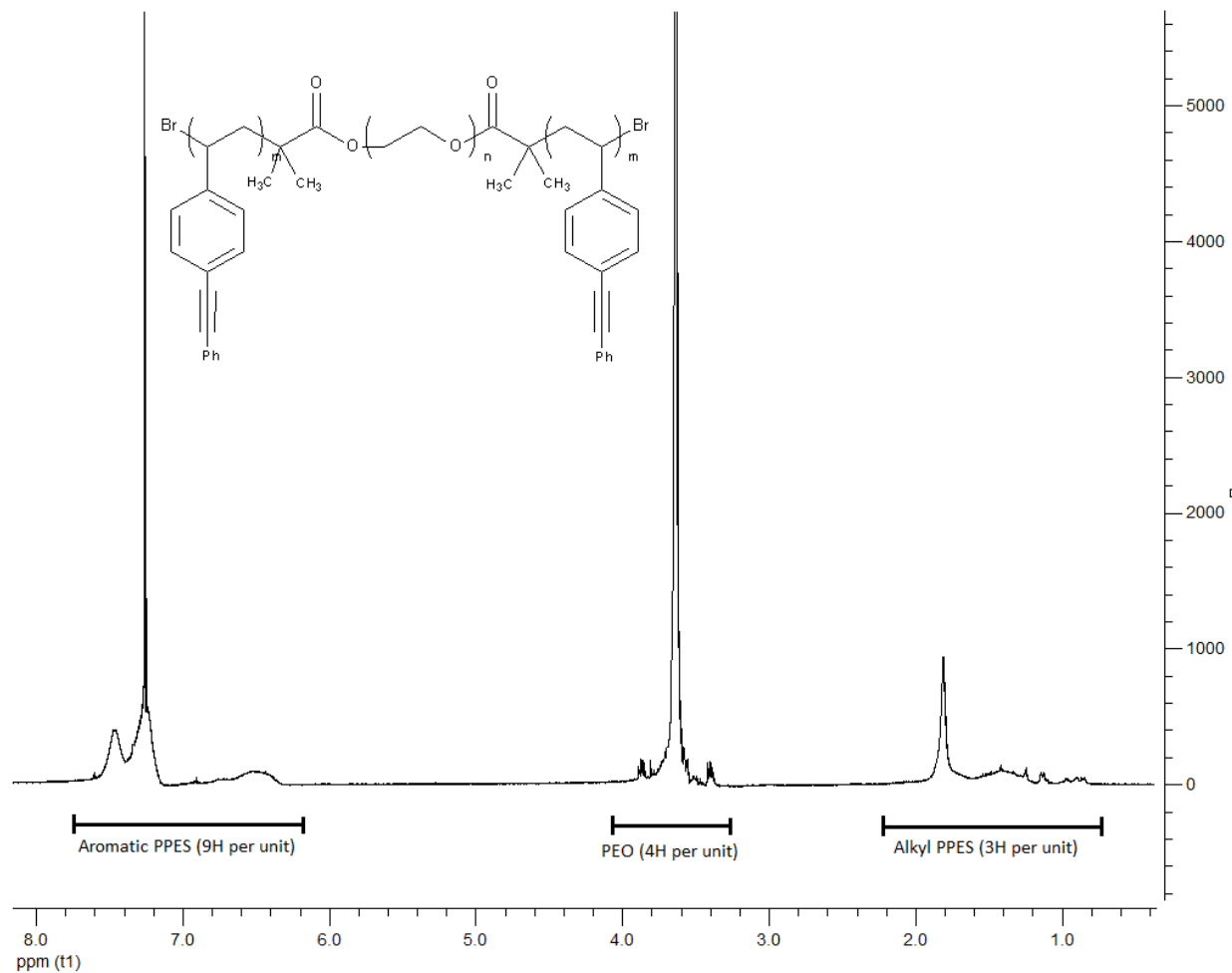**Figure 15:** ^{1}H NMR spectrum of triblock copolymer sample **A7** (PPES$_{12}$-PEO$_{227}$-PPES$_{12}$). Molecular weight of the polymer is calculated by comparison of PEO signal to PPES signals. The aromatic PPES signal overlaps with the CDCl$_3$ solvent peak and the alkyl PPES signal overlaps with signals for both water and the 12 methyl group protons.

This calculation is performed by setting the integration area of the PEO signal equal to the number of repeating CH_2 protons present in 10,000 g/mol worth of PEO (~227 units, ~910 protons). The areas of the PPES signals were then compared to the area of the PEO signal to calculate a total number of PPES protons, and thus an average number of PPES units per copolymer molecule. In the spectrum shown in Figure 15, the aromatic PPES signal overlaps with the solvent peak for $CDCl_3$ and the alkyl PPES signal overlaps with peaks for both water and the 12 methyl protons. These overlaps cause error in the molecular weight calculations that must be taken into account. An easy fix for this would be the use of CD_2Cl_2 to avoid the overlap with the aromatic PPES signals. Results of these trials are shown in Table 1.

Table 1: Results for PPES-b-PEO-b-PPES triblock copolymers synthesized by ATRP using PEO10k macroinitiator.

Sample	ligand	Time (hours)	Temp (°C)	[CuBr]/ [Alkyl Halide]	[Monomer]/ [Initiator]	M_n NMR (g/mol)	M_n PES (g/mol)	Conversion %
A2	bipy	20	110	2.50	121	33000	22800	92
A3	bipy	20	110	1.13	20	12000	1800	44
A4	bipy	20	110	2.36	35	12500	2300	32
A5	bipy	20	110	1.81	36	11000	800	11
A7	bipy	20	110	3.02	36	15000	4800	65
A8	bipy	20	110	3.10	20	13400	3200	77
B1	PMDETA	3	110	2.01	37	15000	4800	63
B3	PMDETA	3	90	1.48	38	12000	1800	24
B4	PMDETA	3	110	1.70	99	16200	6000	30

M_n NMR was calculated from ^{1}H NMR spectra of pure products by comparison of PEO signals to PPES signals. % Conversion was estimated based on molecular weight calculations.

Trials **A4** and **A5** show relatively low conversions. The likely cause of this is experimental error with regards to degassing or delivering CuBr to the reaction mixture, so higher levels of CuBr were used in trials **A7** and **A8**. In trials **B1**-**B4**, the CuBr was added to the

reaction mixture after degassing with two freeze-pump-thaw cycles instead of adding it along with all other components before any degassing. Trial **B3** was run at 90 °C to test the effects of lowering the reaction temperature, and resulted in a low conversion within the same time frame as trials performed at 110 °C.

Addition of cobalt carbonyl to these polymers is a relatively simple procedure. The polymers were mixed in solution with dicobalt octacarbonyl (slight excess) and stirred for at least an hour. These reactions were carried out in a dry glove box under N_2 due to the pyrophoric and toxic nature of $Co_2(CO)_8$. The product obtained from precipitation was a dark brown powder or glassy solid. Precipitation was usually performed twice to obtain a neat powder. Upon first precipitations, the products were usually obtained as a thick, sludgy substance. This problem seemed to be caused by the toluene sticking to the polymers and was later solved by carrying out the metallation reactions in dry chloroform.

In order to examine the self assembled structures of copolymer samples, transmission electron microscopy (TEM) was used. This technique involves the imaging of samples by passing electrons through them onto a fluorescent screen or into a detection system. The instrument used allows for magnification up to 200,000 times. Images of samples **A8** ($PPES_8$-PEO_{227}-$PPES_8$) and **A2** ($PPES_{55}$-PEO_{227}-$PPES_{55}$) were taken. The choice of solvent for sample preparation is important, as the solubility of the sample and its ability to self-assemble in solution must be taken into account. TEM preparation for previous group work mentions casting cobalt-polymer adducts from toluene.[15] Research on similar polymers showed self-assembly occurring in solvent mixtures of DMF and toluene,[19] so this solvent mixture was used to prepare sample **A2**. Images for **A2** show clearly visible spherical structures ranging from 15-40 nm in diameter (Figure 16). The dark spots correspond to areas where cobalt is present in the sample (the alkyne

functional blocks), so the lighter areas should be the PEO blocks. These images are shown in

Figures 16-18.
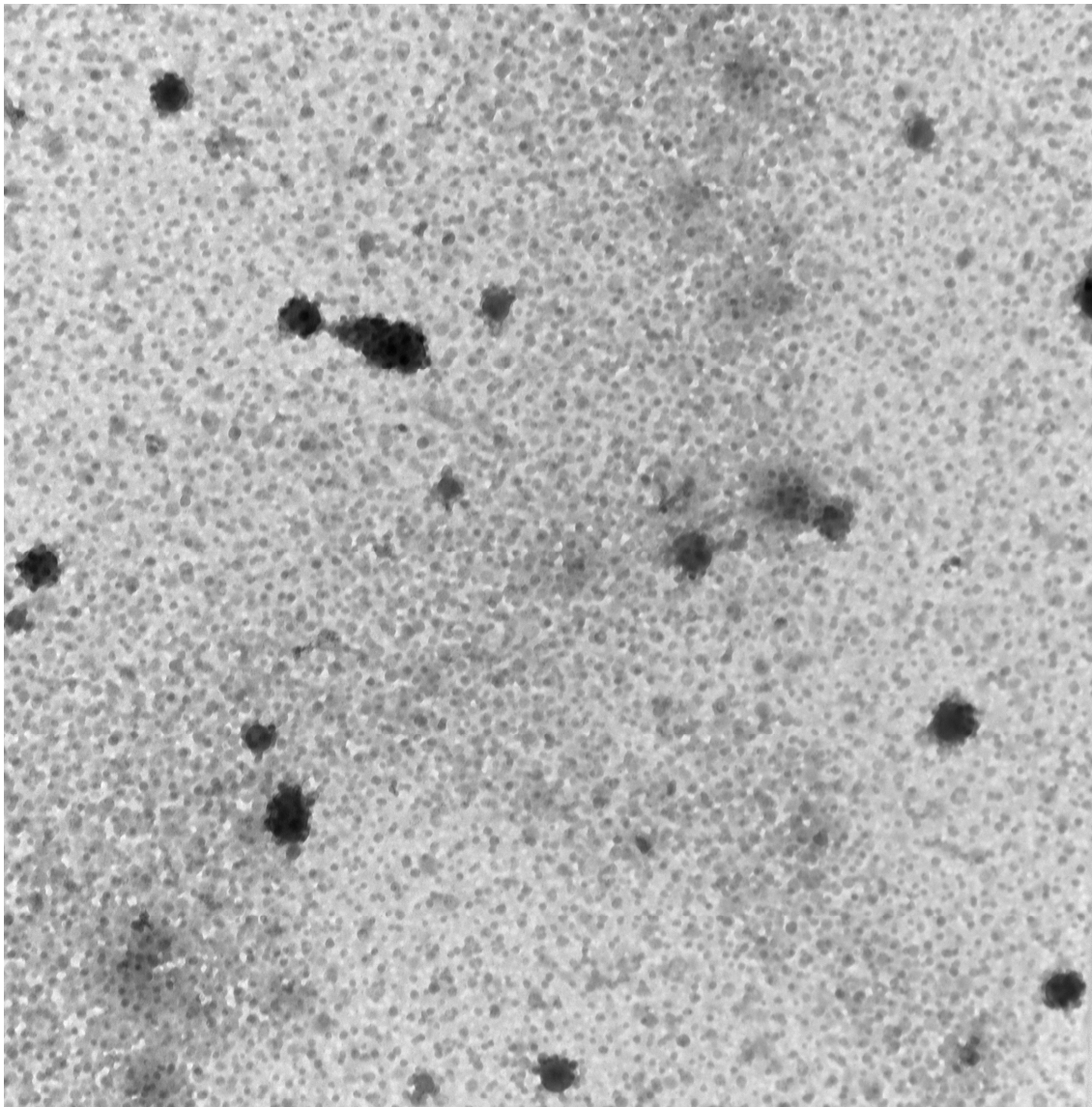
Oct6_005
Laura-1 B3
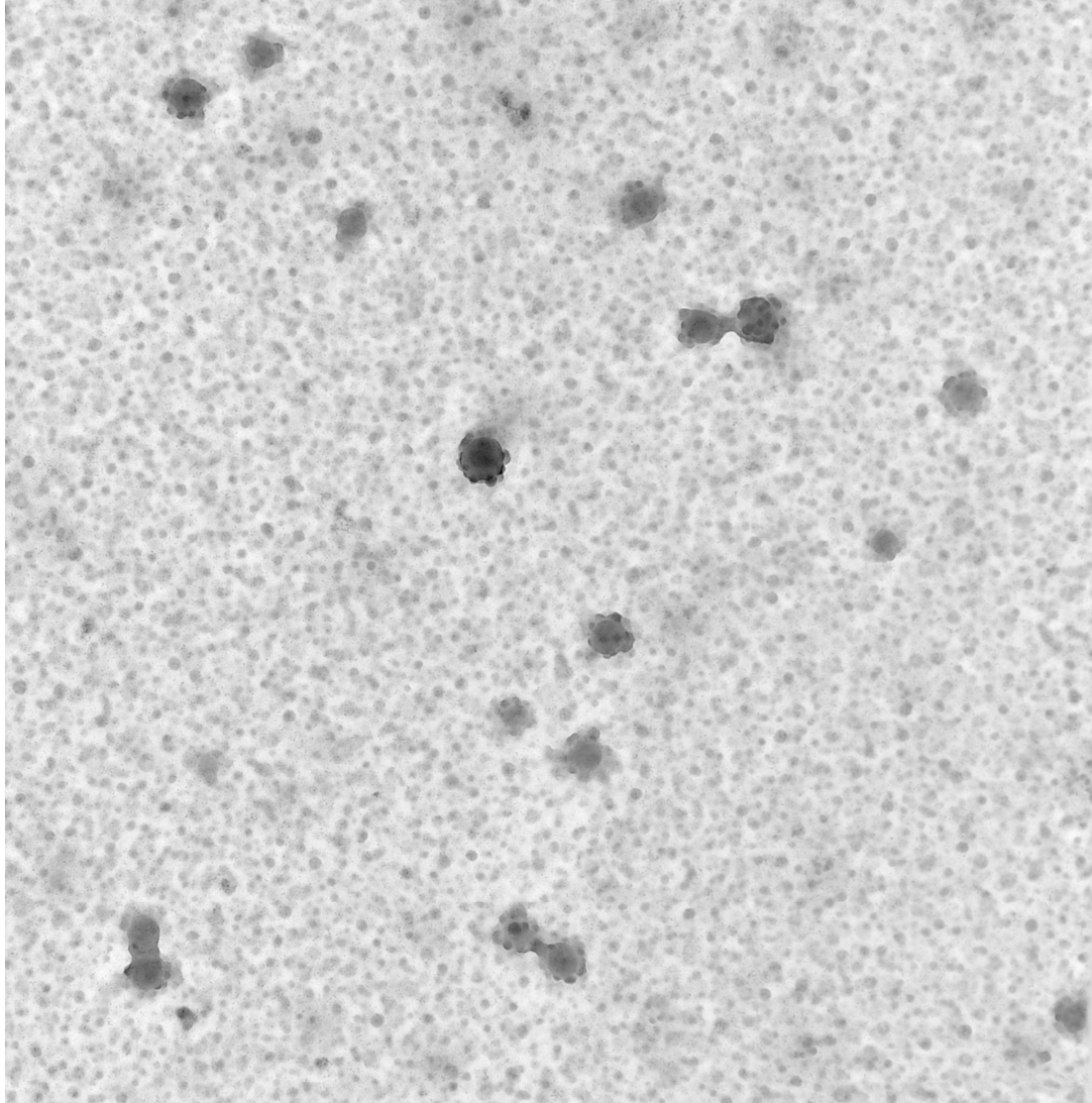Print Mag: 46000x @ 7.0 in
11:03:47 a 10/06/10

500 nm
HV=80.0kV
Direct Mag: 30000x
Tilt:0.02
AMT Camera System

Figure 16: TEM image of triblock copolymer sample **A2** (PPES$_{55}$-PEO$_{227}$-PPES$_{55}$). Magnification at 30,000x.
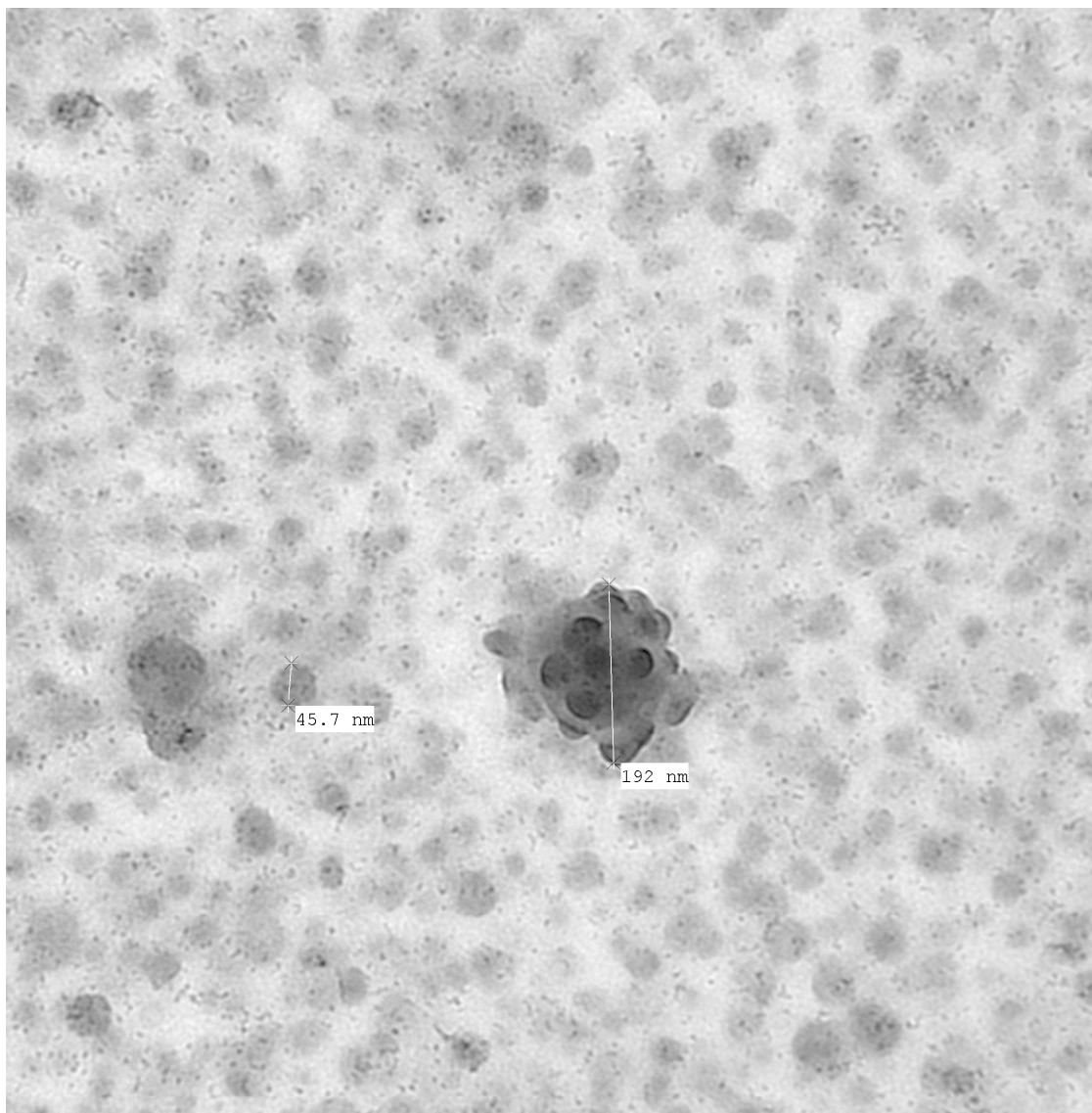
Nov2_004
Print Mag: 46000x @ 7.0 in

500 nm

HV=80.0kV
Direct Mag: 30000x
AMT Camera System

Figure 17: TEM image of triblock copolymer sample **A2** (PPES$_{55}$-PEO$_{227}$-PPES$_{55}$) after heating copper grid at 100 ℃ for 1 hour. Magnification at 30,000x.

Figure 18: TEM image of triblock copolymer sample **A2** (PPES$_{55}$-PEO$_{227}$-PPES$_{55}$) after heating copper grid at 100 ^{0}C for 1 hour. Magnified 98,000x to show detail of a larger structure.

Images of **A2** after heating look similar, though the details in the larger particles became more easily distinguishable (Figures 17 and 18). **A8**, however, was cast from pure DMF at a much lower concentration, and shows small dark spots spread around without any clearly defined structures visible.

Several samples of triblock copolymers were used to test for hydrogel formation. The samples were cast as thin films to which water was added (to give concentrations of 100 mg/mL, 10% polymer by weight) and allowed to sit for several hours. Samples **A7**, **A8**, **B1**, **B4**, and the cobalt carbonyl adduct of **B1** were all successful in the formation of hydrogels. Sample **A2** failed to form a gel under the same conditions, likely due to its hydrophobic PPES blocks being too long. Photographs of samples **B1** and **B4** before and after gelation are shown in Figure 19, and a photograph of the powder and gel of cobalt adduct of **B1** is shown in Figure 20. None of the polymers used to form these gels had been heat-treated to induce cross-linking. Without cross-linking, such gels would not be stable due to the equilibrium between polymers and micelles (shown in Figure 2). Cross-linking would cause the formation of micelles to be permanent, allowing the hydrogels to hold their structure in dilute aqueous environments.
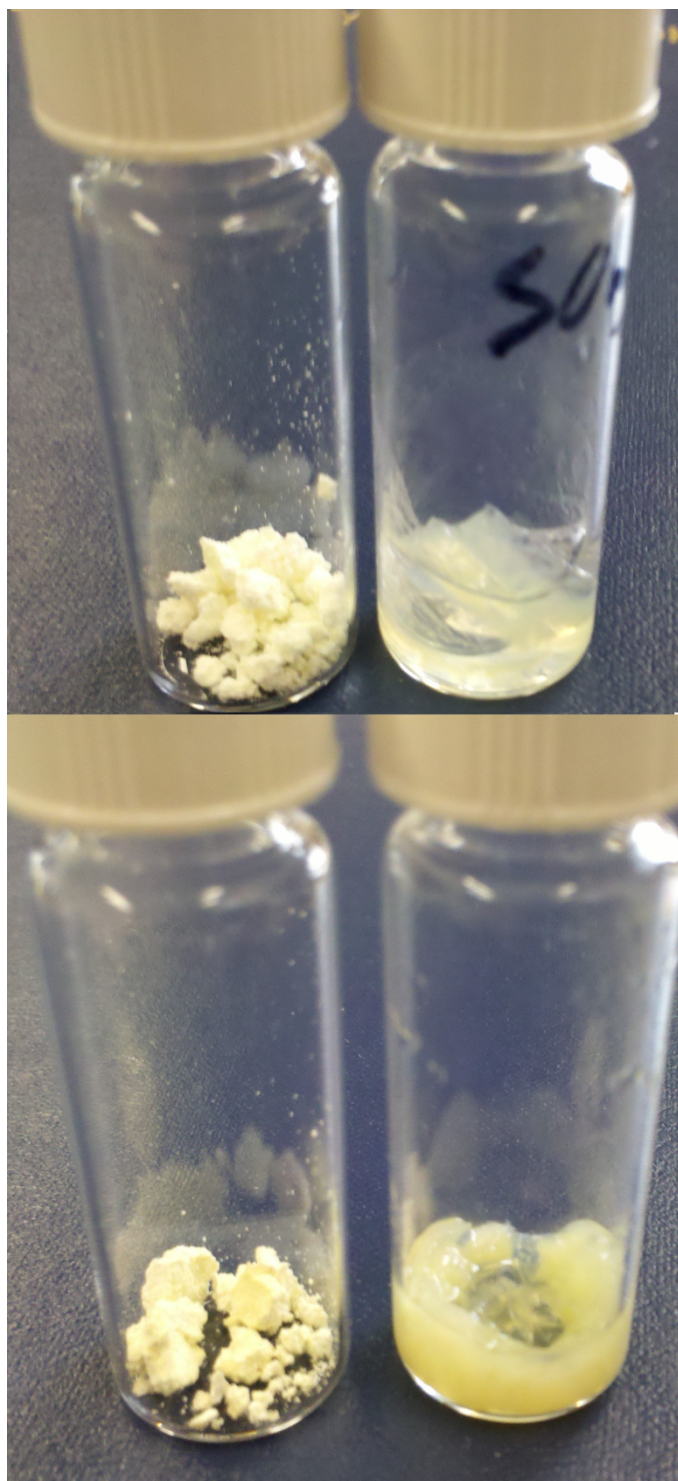
Figure 19: 50 mg of triblock copolymers **B1** (PPES$_{12}$-PEO$_{227}$-PPES$_{12}$, above) and **B4** (PPES$_{15}$-PEO$_{227}$-PPES$_{15}$, below) as powder and as hydrogels. Gels contain ~10% polymer by weight.
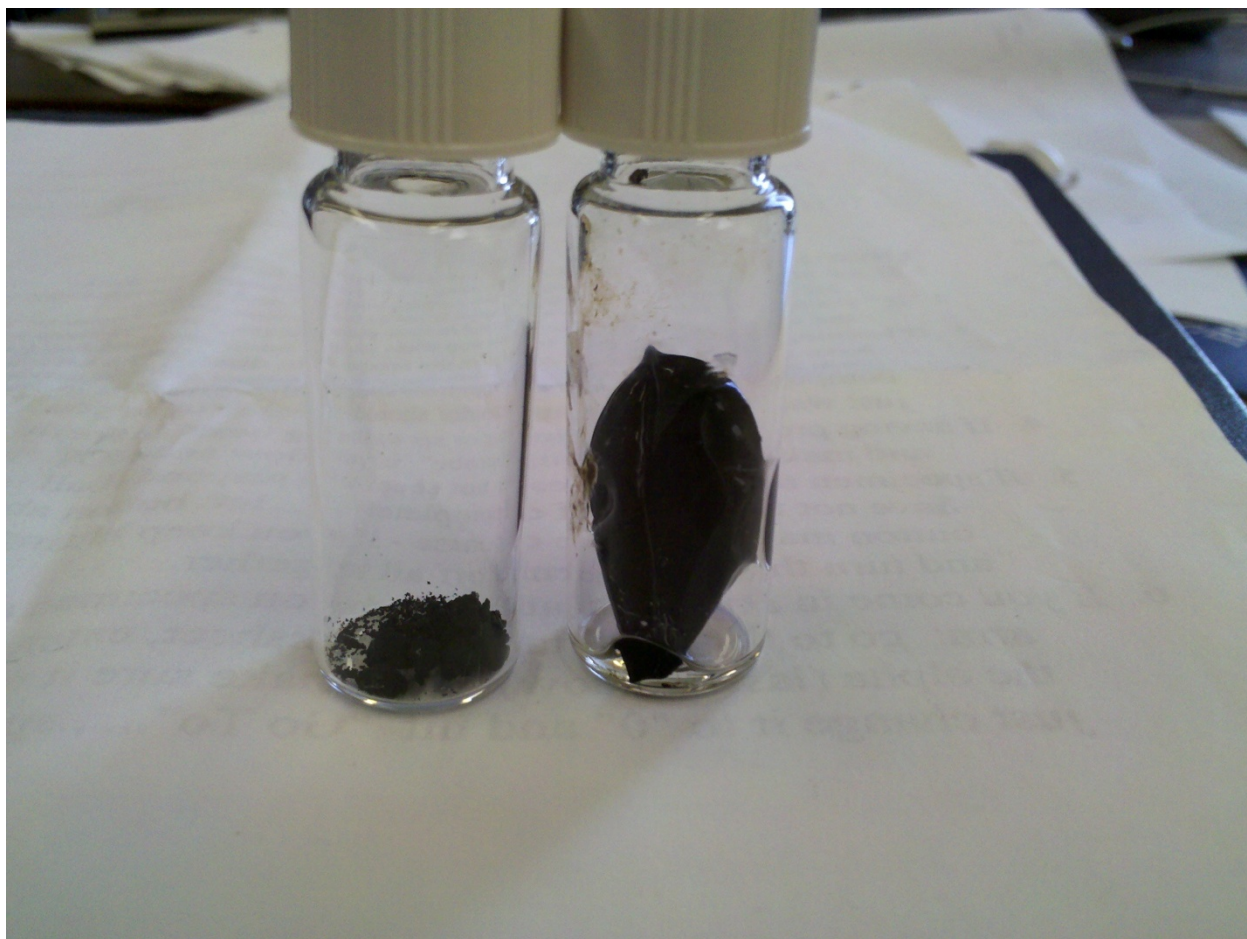
Figure 20: 100 mg of triblock copolymer **B1** (PPES$_{12}$-PEO$_{227}$-PPES$_{12}$) cobalt carbonyl adduct as a powder and as a hydrogel containing ~10% polymer by weight

Diblock Copolymers

Synthesis of the MPEO5k macroinitiator was confirmed by ^{1}H NMR spectroscopy; the spectrum was in agreement with the literature.[11] ATRP trials were carried out using the same procedure used for the synthesis of triblock polymers, using the PMDETA ligand with CuBr, in anisole solution, and with reaction temperatures of 110 °C. Analysis of diblock copolymer products was performed with ^{1}H NMR spectroscopy of crude and pure products and by GPC of pure products. GPC analysis was performed using polystyrene standards, which may cause

inaccurate results for the molecular weights of PEO-based polymers (due to the chemical difference between PEO and PS). Despite possibly inaccurate M_n calculations, GPC was still useful for measuring the polydispersities of these samples. ^{1}H NMR spectra were used to calculate molecular weights using the same method as for the triblock copolymers. For all polymers in the **C** series of trials (Table 2), samples of crude product were taken from the reaction mixture before precipitation and analyzed by ^{1}H NMR spectroscopy. These crude products still contained the unreacted monomer from the ATRP reaction, and the integration of the vinyl signals in the ^{1}H NMR spectrum of PES can be compared to the integration of the signal for the same hydrogens present in the copolymer. Comparison of these two signals can give an estimate of conversion of monomer to polymer. The integral of the peaks for the cis and trans vinylic protons (appearing at 5.3 and 5.7 ppm) in 4-PES monomer can be compared to their corresponding polymer signal, which has shifted to the alkyl region between 0.8 and 2.2 ppm. The ratio of these signals can be used to estimate the percent of monomer conversion, which can be used to calculate a theoretical molecular weight for a given polymer sample. This is illustrated in Figure 21.
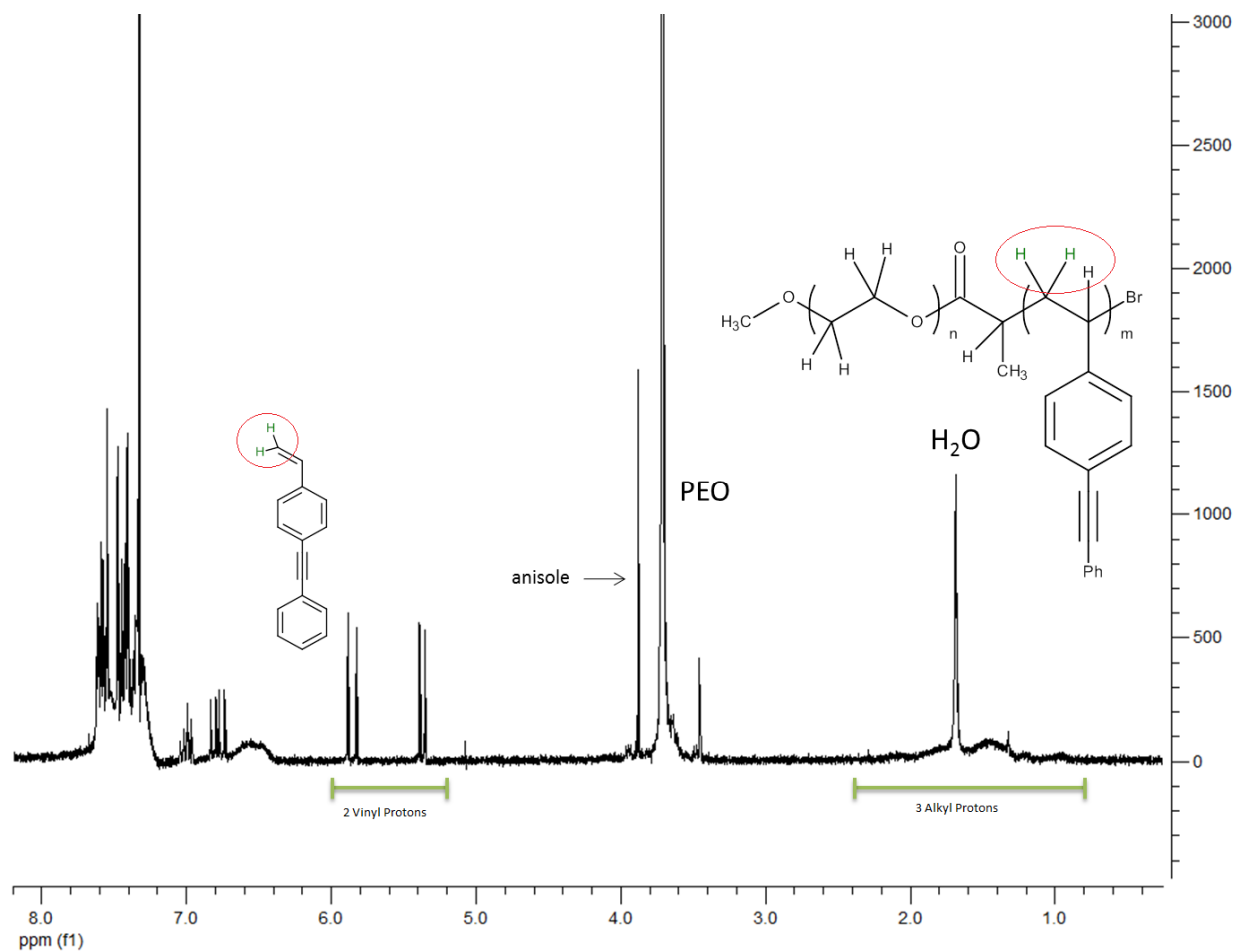
Figure 21: ^{1}H NMR spectrum for crude product of PEO-b-PPES diblock copolymer sample **C9**. The circled protons correspond to those present in the peaks being integrated. The cis and trans vinyl protons are highlighted in green to show their location in the monomer and polymer structures.

The average molecular weights of polymers were also estimated by the comparison of PEO signals to PPES signals in pure polymer samples (same method as used for triblock copolymers). The calculated values for M_n NMR and M_n Theory, as well as the M_n determined from GPC, are shown in Table 2.

Table 2: Results for PEO-b-PPES diblock copolymers synthesized by ATRP

Sample	Time (hours)	[CuBr]/[PEO]	[Monomer]/ [Initiator]	Conversion %	M_n Theory (g/mol)	M_n NMR (g/mol)	M_n GPC (g/mol)	M_w/M_n
C5	18	2.47	7	92	6500	7000	6500	1.15
C6	3	2.74	8	82	6400	7300	6400	1.13
C7	3	2.59	21	80	8400	9100	7700	1.15
C8	3	2.83	35	76	10000	10800	9300	1.14
C9	3	3.08	36	78	10300	11600	8600	1.13
C11	5	1.85	51	67	12000	12300	10400	1.24

Trials were performed at 110 °C using PMDETA ligand. M_n Theory is calculated based on monomer conversion. M_n NMR is based on ^{1}H NMR spectra of pure products. M_n GPC and polydispersity M_w/M_n are calculated using polystyrene standards.

These trials were all performed at 110 °C in anisole at 0.2 g/mL overall concentration. M_n values calculated from conversion (M_n Theory) and from ^{1}H NMR spectra (M_n NMR) are in agreement and polydispersities are fairly narrow. The M_n from GPC seems to match well with theory and NMR values on a few samples, but this is likely coincidental.

Cobalt addition onto PEO-b-PPES diblock samples was performed in dry chloroform as opposed to dry toluene, as was used for PPES-b-PEO-b-PPES polymers. This change was made for two reasons: the polymers are more soluble in chloroform than in toluene, and to avoid the aforementioned problem with needing to precipitate the cobalt bound polymers multiple times when using toluene.

In order to synthesize diblock copolymers PS-b-PPES, two synthetic approaches were considered. One approach involved the use of a single ATRP reaction mixture. In this mixture, either styrene or 4-PES is polymerized first to form a homopolymer of desired chain length. Afterwards, the second monomer is added to the reaction mixture in order to begin forming the second block onto the ends of the first block. The second approach involved utilizing the ability of ATRP to preserve the active endgroups of its products. This would allow for the use of isolated polystyrene homopolymer as a macroinitiator onto which PPES blocks could be polymerized. The second approach was chosen for use because it would provide better control over the process of polymerization. The block length of PS could be kept constant with variations only occurring in the length of PPES blocks. Another problem with the first approach is that the formation of the second blocks of polymer would not be uniform in their composition, due to remaining quantities of the first monomer.

PS was also chosen for use as a macroinitiator instead of PPES because its use in this method of block copolymer formation is well documented.[20, 21] ATRP of styrene was performed in bulk at 100 $^\circ$C using a CuBr/PMDETA catalyst complex system. Two trials were performed under similar conditions, where one was allowed to run for ~18 hours (**PS1**) and one was run for 3 hours (**PS2**). The reaction mixture for trial **PS1** had solidified by the end of the 18 hours. GPC data showed the polystyrene homopolymer to have a M_n of approximately 7500 g/mol (>90% conversion) and a very narrow M_w/M_n of 1.06. GPC data for trial **PS2** showed a M_n of 4400 (58% conversion) and a M_w/M_n of 1.07. ^{1}H NMR analysis shows polymeric growth in the appearance of strong broad signals in the aromatic and alkyl regions. Quantitative measurements could not be made, however, due to the lack of usable reference peaks from the initiator structure. The signals from the 1-(bromoethyl)benzene initiator are buried under the

polystyrene signals. The use of a different initiator could solve this problem, such as an α-bromoester like methyl 2-bromopropionate (protons adjacent to an ester should be shifted into a range suitable for reference). An internal standard could also be added to the reaction mixture; a chemical whose signal in the ^{1}H NMR spectrum would not overlap the polystyrene signals and could be quantitatively compared to the polystyrene signals to perform molecular weight calculations.

Polystyrene macroinitiator **PS2** ($M_n = 4400$) was chosen for trials to form diblock copolymers with PPES. Products were analyzed by GPC to check for growth in molecular weight compared to pure **PS2**. ^{1}H NMR analysis was once again not useful for analyzing these block copolymers due to the overlap of PPES signals with PS signals as well as the lack of reference peaks. Results for several trials are shown in Table 3.

Table 3: Results for PS-b-PPES diblock copolymers synthesized by ATRP.

Sample	Time (hours)	Temp (°C)	[CuBr]/[PS]	[Monomer]/ [Initiator]	Conversion %	M_n GPC (g/mol)	M_w/M_n
D1	3	110	3.69	38	43	10800	1.18
D3	5	110	1.88	21	74	7600	1.13
D5	5	110	1.90	42	98	12800	1.24
D6	5	110	2.45	32	ND	11300	1.23
D7	4	100	1.63	27	29	6000	1.10

Sample D1 was synthesized using a PS macroinitiator of M_n=7500 g/mol. All other samples were synthesized using PS macroinitiator of M_n=4400 g/mol. Conversions were estimated based on molecular weights of products from GPC. Conversion % for sample **D6** was calculated as being over 100% and is labeled as "ND" (not determined), which illustrates a problem with the method being used to estimate conversion.

Sample **D1** uses polystyrene macroinitiator **PS1** (M_n=7500 g/mol) whereas all other samples use **PS2** (M_n=4400 g/mol). Some problems are evident with these results.

Polydispersities for **D5** and **D6** are slightly higher than for other products, but are still reasonable. Conversion calculations for **D6** gave over 100%, showing a major flaw in using GPC M_n results to estimate the conversion of monomer. Results for **D5** likely suffer from the same problem, as a 98% conversion seems unreasonably high. This illustrates the problem with estimating conversion from the GPC estimated molecular weight. Both trials **D5** and **D6** included the use of high concentrations of 4-PES monomer relative to other trials, which may cause issues in control over polymerization. More trials would have to be run in order to investigate. Use of a different initiator or an internal standard when synthesizing PS homopolymer should allow for ^{1}H NMR determination of molecular weights, which would be very useful in determining more accurate conversion values.

Addition of cobalt carbonyl to PS-b-PPES polymers was performed in the same fashion as for PEO block copolymers and also yielded dark brown powders.

Conclusion and Future Work

Amphiphilic triblock copolymer PPES-b-PEO-b-PPES and diblock copolymers PEO-b-PPES and PS-b-PPES were successfully synthesized and characterized by ^{1}H NMR and GPC. Addition of cobalt carbonyl to alkyne functional blocks was also successful. Investigation of the magnetic properties would require heating polymer samples in bulk or in solution, followed by IR spectroscopy to confirm loss of carbonyl ligands. Further studies involving TEM and SAXS are required to determine the structures these polymers. Additionally, synthesizing a broader
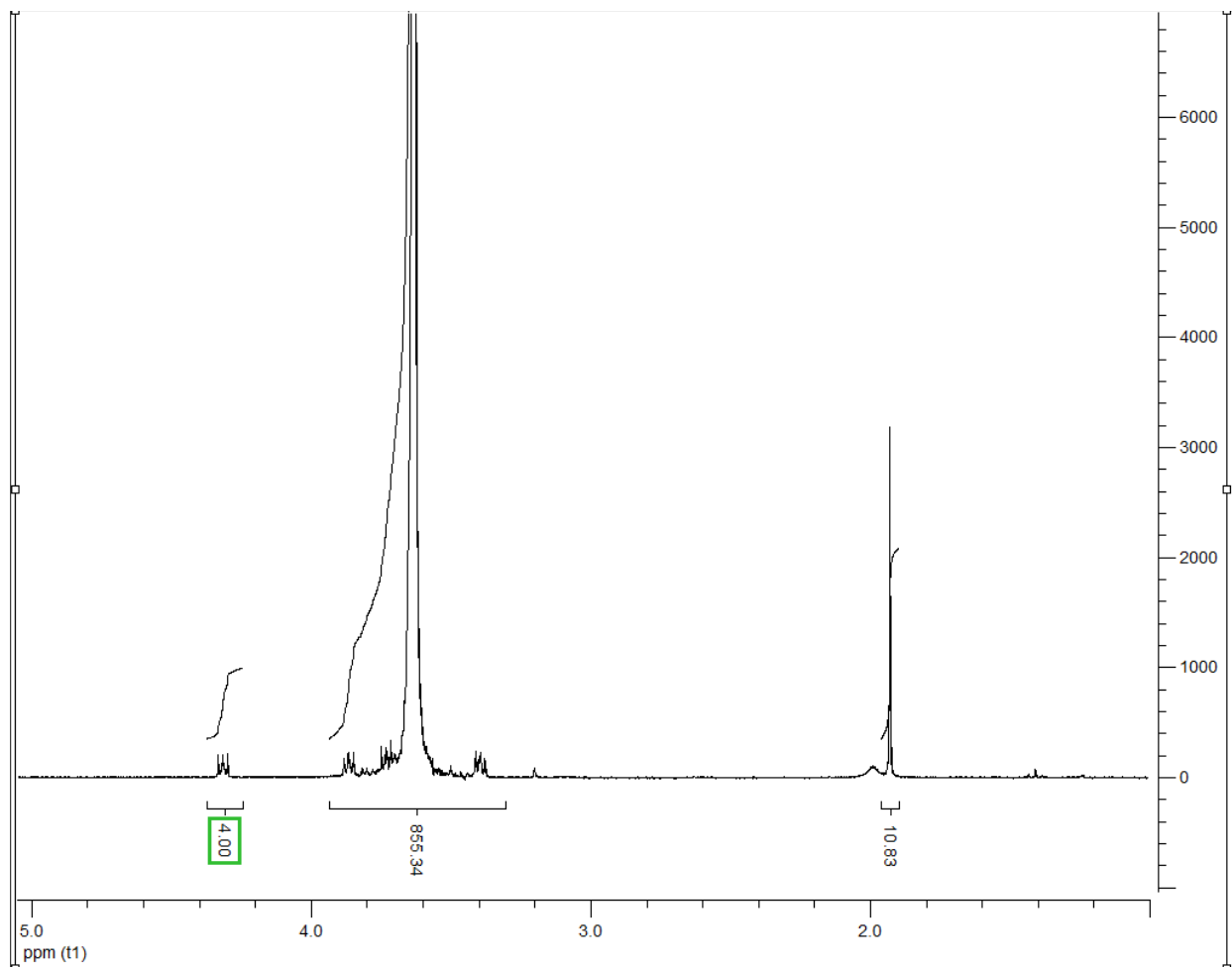
range of molecular weights would be necessary for full studies of structure as a function of relative block length.
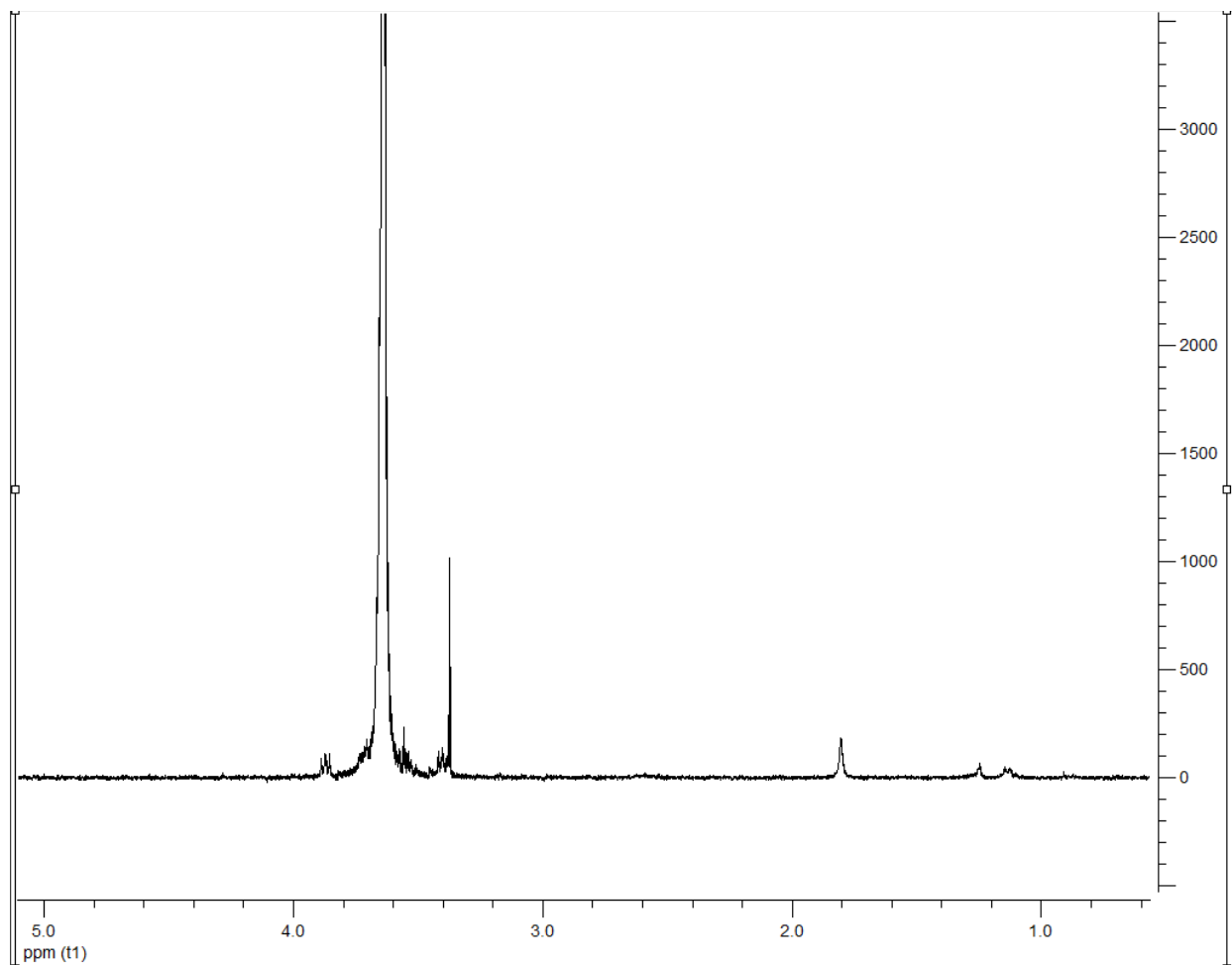
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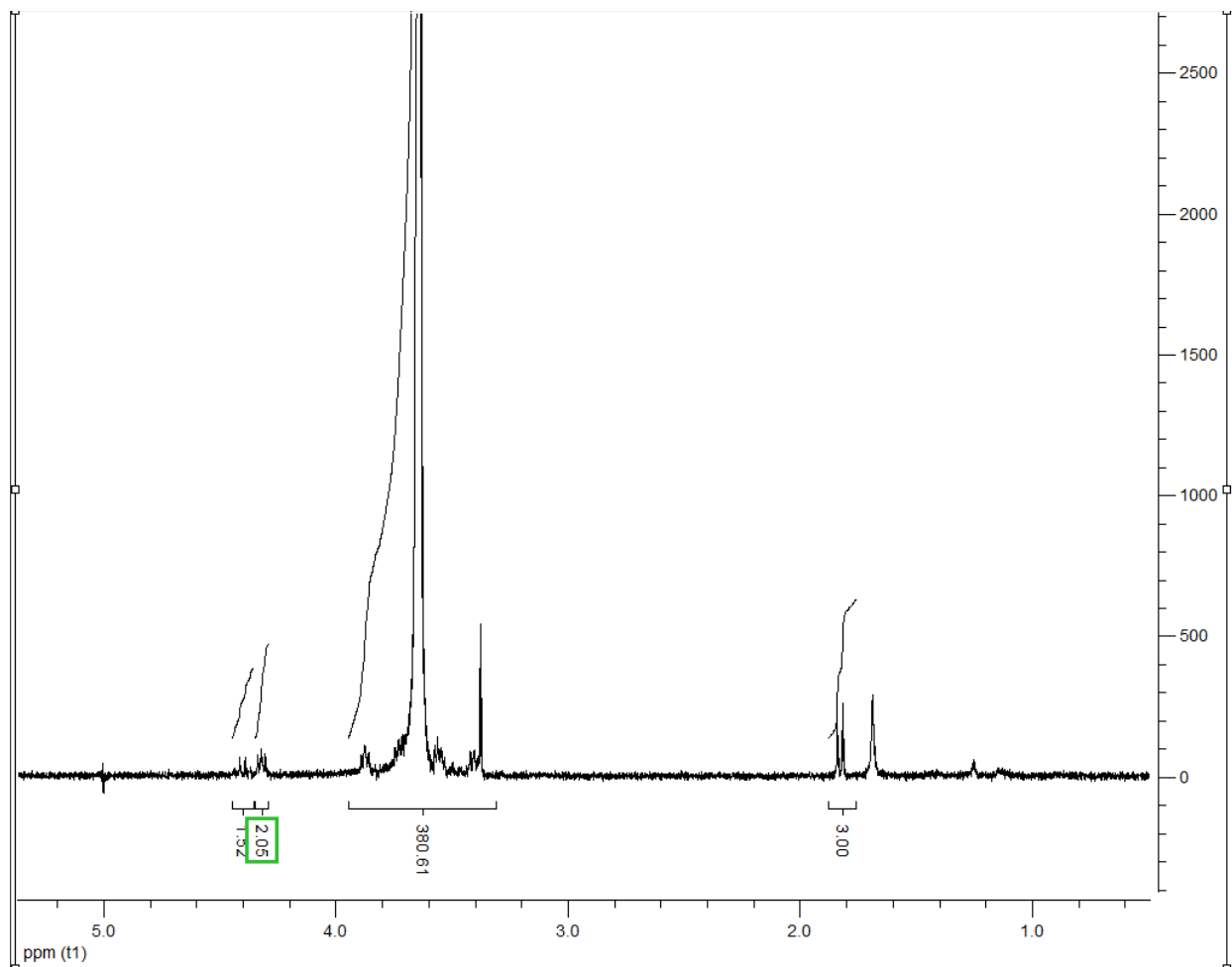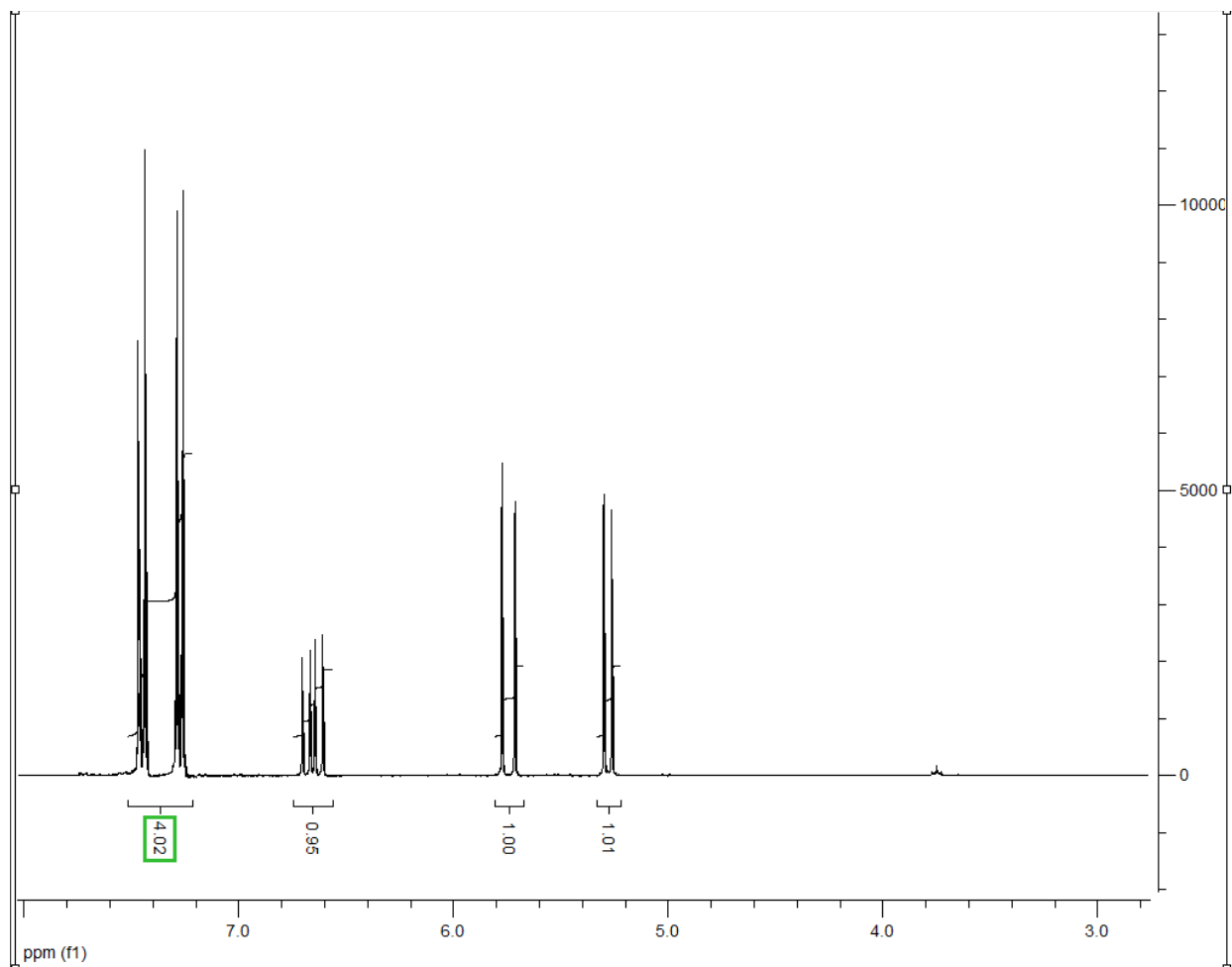
Appendix:

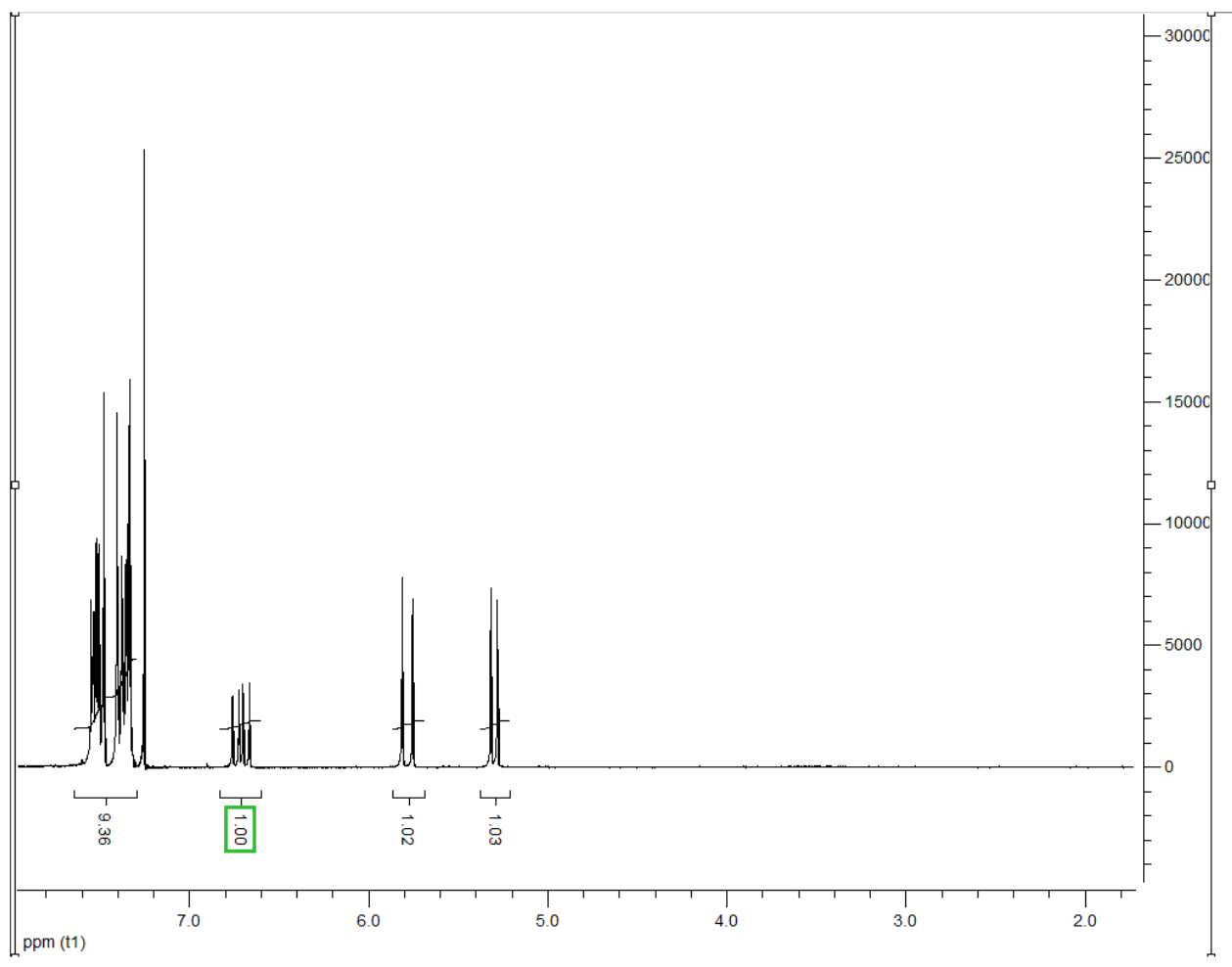^{1}H NMR spectrum for PEO10k macroinitiator

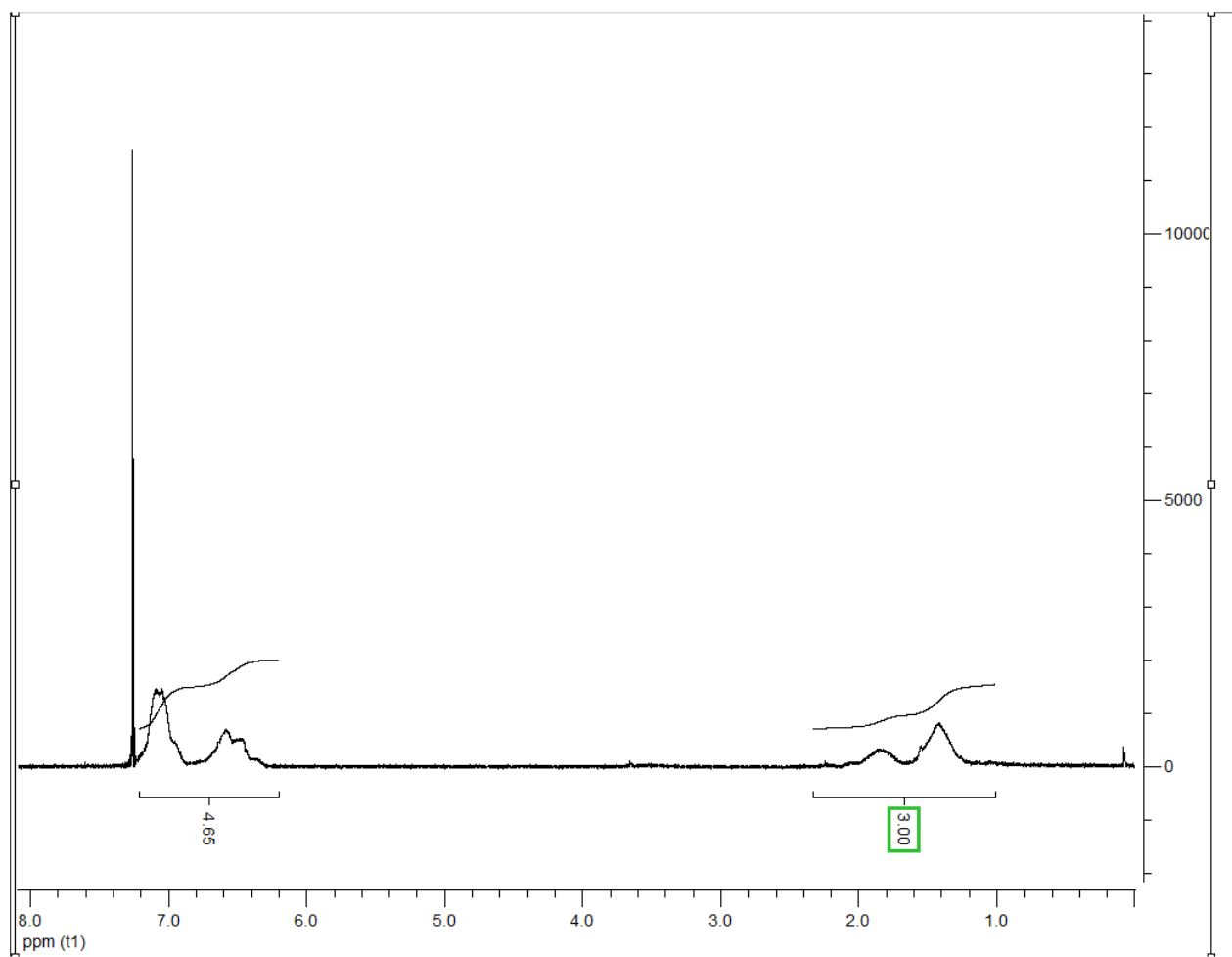^{1}H NMR spectrum for PEO5k monomethyl ether

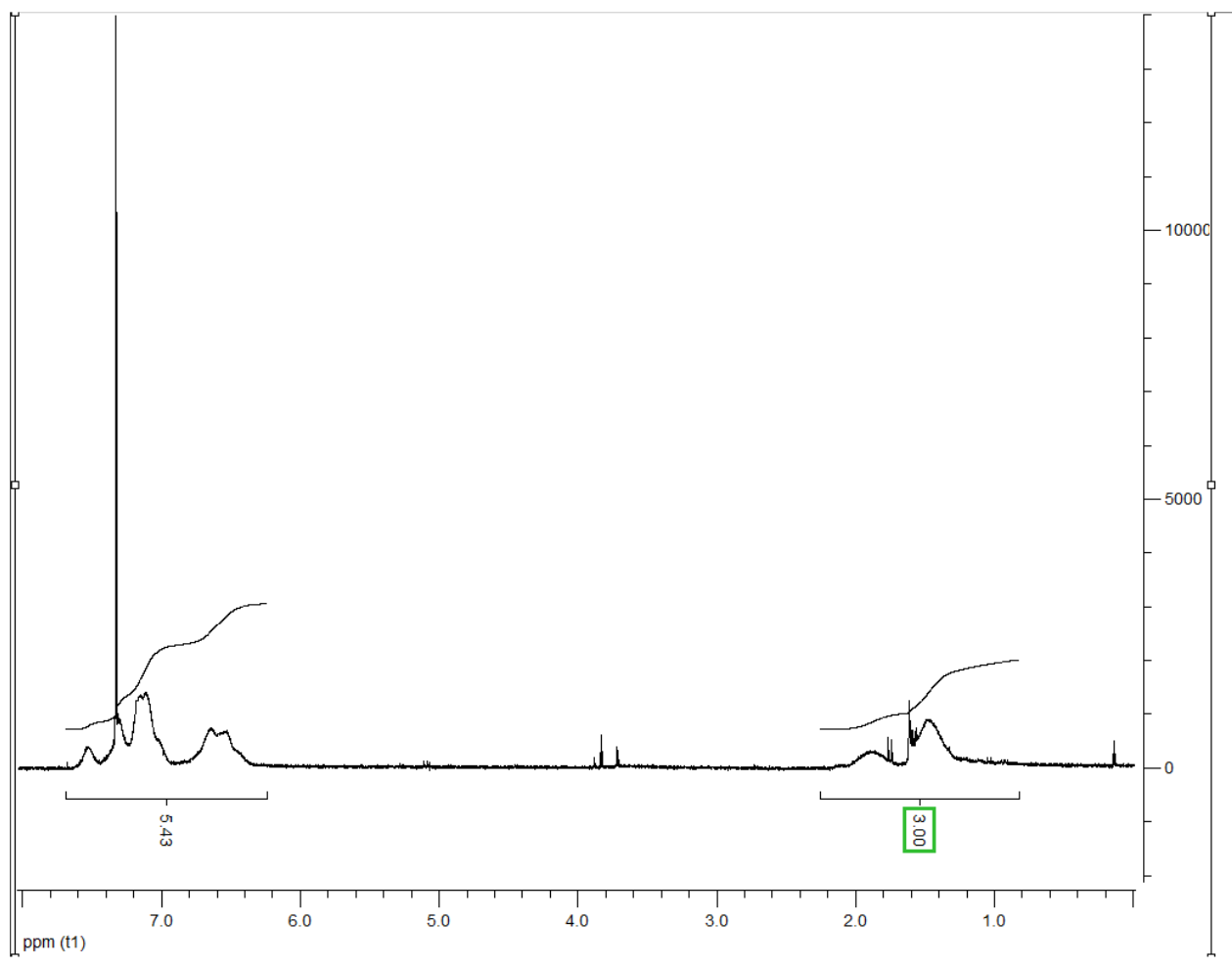^{1}H NMR spectrum for PEO5k macroinitiator

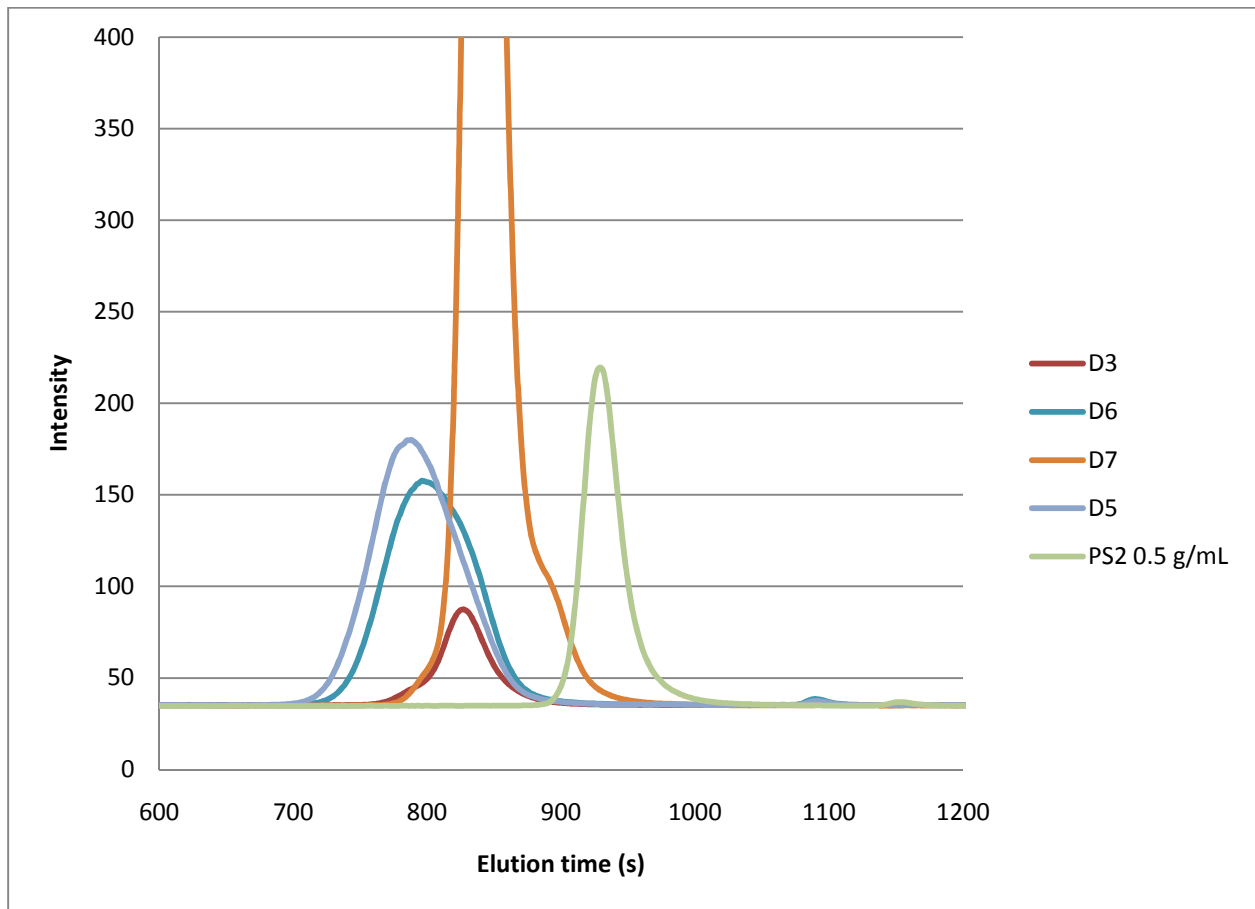^{1}H NMR spectrum for 4-bromostyrene

^{1}H NMR spectrum for 4-PES

^{1}H NMR Spectrum for polystyrene macroinitiator **PS1** (M_n=7500, M_w/M_n=1.06)

^{1}H NMR Spectrum for diblock copolymer sample PS$_{72}$-PPES$_{16}$ (**D1**)

GPC traces for polystyrene macroinitiator **PS2** (M_n=4400, M_w/M_n=1.07) and PS-*b*-PPES copolymers synthesized from this initiator. Copolymer samples are further to the left than the macroinitiator and are broader, indicating higher molecular weights and broader polydispersities.