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(72) Inventeurs/Inventors:  
COATES, GEOFFREY W., US;  
ALLEN, SCOTT D., US;  
COHEN, CLAIRE, US;  
PERETTI, KATHRYN, US;  
AJIRO, HIROHARU, JP

(73) Propriétaire/Owner:  
CORNELL RESEARCH FOUNDATION, INC., US

(74) Agent: RIDOUT & MAYBEE LLP

(54) Titre : CATALYSEUR SPECIFIQUE ISOTACTIQUE POUR LA PRODUCTION INDIRECTE D'UN OXYDE DE POLYPROPYLENE HAUTEMENT ISOTACTIQUE OU D'UN OXYDE DE POLYBUTYLENE HAUTEMENT ISOTACTIQUE  
(54) Title: ISOTACTIC SPECIFIC CATALYST FOR DIRECT PRODUCTION OF HIGHLY ISOTACTIC POLY(PROPYLENE OXIDE) OR HIGHLY ISOTACTIC POLY(BUTYLENE OXIDE)

(57) Abrégé/Abstract:

(Salph or methoxy salph) Co (initiating ligand) catalyze homopolymerizing rac-PO to produce pure highly isotactic PPO and rac-1-butylene oxide to produce pure isotactic poly(butylene oxide). A product is unfractionated isotactic PPO of m-dyad content > 81%, normally at least 99%.

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11/454,945 19 June 2006 (19.06.2006) US(71) Applicant: **CORNELL RESEARCH FOUNDATION, INC.** [US/US]; 20 Thornwood Drive, Suite 105, Ithaca, New York 14850 (US).(72) Inventors: **COATES, Geoffrey, W.**; 15 Beckett Way, Ithaca, New York 14850 (US). **ALLEN, Scott, D.**; 442 N. Titus Avenue, Ithaca, New York 14850 (US). **COHEN, Claire**; 820 Pine Valley Lane, #104, Toledo, Ohio 43615 (US). **PERETTI, Kathryn**; 120 Turkey Hill Road, Apt.1, Ithaca, New York 14850 (US). **AJIRO, Hiroharu**; Gobankan II-203, Onohara Higashi 5-8-48, Minoh City, Osaka, 562-0031 (JP).(74) Agents: **SPECTOR, Eric, S.** et al.; BACON & THOMAS, PLLC, 625 Slaters Lane - 4th Floor, Alexandria, VA 22314 (US).(84) **Designated States** (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IS, IT, LT, LU, LV, MC, NL, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).**Published:**

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(54) Title: ISOTACTIC SPECIFIC CATALYST FOR DIRECT PRODUCTION OF HIGHLY ISOTACTIC POLY (PROPYLENE OXIDE) OR HIGHLY ISOTACTIC POLY (BUTYLENE OXIDE)

(57) Abstract: (Salph or methoxy salph) Co (initiating ligand) catalyze homopolymerizing rac-PO to produce pure highly isotactic PPO and rac-1-butylene oxide to produce pure isotactic poly(butylene oxide). A product is unfractionated isotactic PPO of m-dyad content &gt; 81%, normally at least 99%.

ISOTACTIC SPECIFIC CATALYST FOR DIRECT  
PRODUCTION OF HIGHLY ISOTACTIC POLY(PROPYLENE OXIDE)  
OR HIGHLY ISOTACTIC POLY(BUTYLENE OXIDE)

Background of the Invention

Almost all commercial polypropylenes are highly isotactic rather than atactic since highly isotactic polypropylenes are crystalline and provide structural functionality whereas atactic polypropylenes are amorphous and rubbery. In some cases poly(propylene oxide) is advantageous compared to polypropylene, e.g., in cases where adhering is important (since poly(propylene oxide) adheres better than polypropylene because of the oxygen in the backbone); however, all commercial poly(propylene oxide)s are atactic (and amorphous) and are not suitable for structural functionality and are not resistant to dissolving. On the other hand, isotactic poly(propylene oxide) is crystalline and suitable for structural functionality and is resistant to dissolving.

The reasons why commercial poly(propylene oxide)s are atactic is because of the high expense of optically active propylene oxide and because of the lack of catalysts that can isospecifically polymerize rac-propylene oxide, so that in almost all cases where isotactic poly(propylene oxide)s are synthesized, the product is a mixture

of isotactic and atactic poly(propylene oxide)s. The mixture must be fractionated for recovery of isotactic poly(propylene oxide) e.g., by immersing the admixture in acetone below 0 °C which dissolves atactic poly(propylene oxide) but not isotactic poly(propylene oxide) and fractionation takes time and is expensive.

Catalysts have been developed that produce isotactic poly(propylene oxide) as a sole product (see Yoshino, N., et al., *Macromol. Chem.* 189, 1903-1913 (1988)), but said production requires a period of days and the m-dyad content is below 81%.

A higher dyad content has the advantage of a higher melting point and therefore suitability for higher temperature use.

Moreover, known catalysts that achieve high  $M_n$  provide high polydispersity index (PDI) and those that achieve low PDI provide low  $M_n$ .

As used herein PPO means poly(propylene oxide) and PO means propylene oxide.

### Summary of the Invention

It is an object herein to provide catalysts that directly provide (i.e., without fractionation) highly isotactic PPO from rac-propylene oxide and highly isotactic poly(butylene oxide) from rac-1-butylene oxide and which allow obtaining high  $M_n$  with low PDI.

$M_n$ , i.e., number average molecular weight, and PDI herein are determined using size exclusion chromatography calibrated by polystyrene standards in 1,2,4-trichlorobenzene at 140 °C.

In one embodiment of the invention herein, denoted the first embodiment, there is provided an isotactic specific catalyst useful for rac-propylene oxide polymerization and rac-1-butylene oxide polymerization, namely (salph or methoxy salph) Co (initiating ligand) where salph is N,N'-bis(3,5-di-C<sub>1</sub>-C<sub>4</sub>-alkylsalicylidine)-1,2-benzenediamine or N,N'-bis(3-C<sub>1</sub>-C<sub>4</sub>-alkyl-5-tert-butylsalicylidine)-1,2-benzenediamine. In a preferred case, salph is N,N'-bis(3,5-di-tert-butylsalicylidine)-1,2-benzenediamine and the initiating ligand is an acetate (-OCOR) or alkoxide (-OR) where R = CH<sub>3</sub>.

In another embodiment herein, denoted the second embodiment, the catalyst is made by dissolving (salph) Co or (methoxy salph) Co in methylene chloride, adding

H(initiating ligand) and allowing the methylene chloride of the solution to evaporate in air.

In another embodiment herein, denoted the third embodiment, the invention is directed to a method of producing pure highly isotactic (m-dyad content > 81%, e.g., > 90%, e.g., at least 99%) comprising homopolymerizing rac-PO in the presence of an isospecific, i.e., isotactic specific, catalyst. The m-dyad content is determined herein by  $^{13}\text{C}$  NMR spectroscopy ( $\text{CDCl}_3$ , 125 MHz). As used herein “m-dyad” means meso-dyad. Generally the method comprises homopolymerizing epoxide, e.g.,  $\text{C}_1\text{-C}_{10}$  alkylene oxide in the presence of a Schiff base containing metal complex containing cobalt in the 3+ oxidation state.

In still another embodiment herein, denoted the fourth embodiment, the invention is directed at a method for producing isotactic poly(butylene oxide) comprising the step of polymerizing rac-1-butylene oxide in the presence of an isospecific, i.e. isotactic specific, catalyst.

In another embodiment herein, denoted the fifth embodiment, the invention is directed to isotactic PPO having m-dyad content greater than 81%, e.g., greater than 90%, e.g., at least 99%, and containing polymerization catalyst residue.

In still another embodiment herein, denoted the sixth embodiment, the invention is directed to isotactic PPO having m-dyad content greater than 81%, e.g. > 90%, e.g., at least 99% and containing no residue indicating fractionation of atactic isotactic PPO admixture, e.g., acetone at 0 °C which was used to dissolve atactic PPO in fractionation of atactic isotactic admixture.

In another embodiment herein, denoted the seventh embodiment, the invention is directed to isotactic PPO having m-dyad content greater than 81%, e.g., > 90%, e.g., at least 99%, and  $M_n$  greater than 150,000 g/mol.

In another embodiment herein, denoted the eighth embodiment, the invention is directed to isotactic PPO having m-dyad content greater than 81%, e.g., > 90%, e.g., at least 99%, and PDI less than 2.0.

In another embodiment herein, denoted the ninth embodiment, the invention is directed to isotactic PPO having m-dyad content greater than 81%, e.g., > 90%, e.g., at least 99%, and containing no, i.e., not even a trace of, atactic PPO.

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In another embodiment of the invention herein, denoted the tenth embodiment, the invention is directed to a method of modifying the properties of unfractionated isotactic PPO comprising the step of providing admixtures of non-isotactic PPO with the unfractionated isotactic PPO.

The term "initiating ligand" is used herein to mean any ligand that can ring open an epoxide.

#### Detailed Description

We turn now to the first embodiment of the invention herein which is directed to an isotactic specific catalyst useful for rac-propylene oxide polymerization and rac-1-butylene oxide polymerization. The catalyst is also useful for preparing copolymer of C<sub>2</sub> - C<sub>10</sub> alkylene oxide and CO<sub>2</sub> with less than 10% cyclic alkylene carbonate by-product under the conditions described in U.S. Provisional Patent Application No. 60/616,630 or U.S. Patent Application No. 11/244,231.

The catalyst of the first embodiment is (salph or methoxy salph) Co (initiating ligand).

The catalyst is preferably selected from the group consisting of (salph or methoxy salph) Co (initiating ligand) where the initiating ligand is preferably selected from the group consisting of halogen (e.g., Cl, Br, I), C<sub>1</sub>-C<sub>20</sub> amido, cyano, azide, C<sub>1</sub>-C<sub>20</sub> alkyl carboxylate, including mono-, di- and tricarboxylates and those that are hydroxyl substituted, C<sub>1</sub>-C<sub>20</sub> aryl carboxylate including adamantyl carboxylate, C<sub>1</sub>-C<sub>20</sub> alkoxide and phenoxide and OH.

Examples of these catalysts are (salph) Co OAc where Ac is acetyl, (salph) Co BzOAc where BzOAc is benzylacetoyl, (salph) Co NpOAc where NpOAc is naphthylacetoyl, (salph) CoOMe where OMe is methoxy, and (methoxy salph) CoOAc, where OAc is acetyl where salph is N,N'-bis(3,5-di-tert-butylsalicylidine)-1,2-benzenediamine.

While not being bound by any theory, the origin of isospecificity is considered to arise from aggregates that resist complete dissolution when solvent is added to the crystalline complexes. The achiral cobalt complexes crystallize in a chiral fashion where complexes are related to C<sub>2</sub>-symmetry axes. Upon addition of solvent and/or

epoxide, the complexes partially dissolve, but those that do not have chiral active sites composed of adjacent cobalt centers. These cobalt centers act in concert to isospecifically polymerize chiral epoxides. The complexes exist in a chiral environment due to aggregation or in-situ ligand modification.

We turn now to the second embodiment of the invention which is directed to how isotactic specific catalysts are made; (salph) Co is made as described in Example I hereinafter. Initiating ligand is introduced by dissolving (salph) Co in methylene chloride, adding H (initiating ligand) and allowing the methylene chloride of the solution to evaporate in open air.

The preparation of (salph) CoOAc from (salph) Co is described in detail in Example II hereinafter. To make (salph) CoBzOAc, benzylacetic acid is substituted for the acetic acid in said preparation of Example II. To make (salph) CoNpOAc, naphthylacetic acid is substituted for the acetic acid in said preparation of said Example II. To make (salph) CoOMe, (salph) Co is dissolved in methanol and the methanol of the solution is allowed to evaporate in open air. The preparation of (methoxy salph) CoOAc is described in Example III hereinafter. Methoxy (salph) Co was prepared by adding 3,5-di-tert-butyl-2-hydroxybenzaldehyde to 4-methoxy-1,2-phenylenediamine as described in “Preparation of 3” of Example III to produce product 3 as described in Example III. Said product 3 was converted to (methoxy salph) Co as described in “Preparation of 4” of Example III. To make (methoxy salph) CoOAc, the (methoxy salph) Co is dissolved in methylene chloride, followed by addition of H (initiating ligand), in this case acetic acid, followed by evaporation of the solvent in air as described in Example III.

We turn now to the third embodiment herein directed to a method of producing pure highly isotactic PPO comprising the step of homopolymerizing rac-propylene oxide in the presence of an isospecific, i.e., isotactic specific, catalyst. The isospecific catalysts are those, e.g., of the first and second embodiments herein, i.e., (salph or methoxy salph) Co (initiating ligand). The solvent for reaction is preferably an acyclic ether (e.g., diethyl ether) or an aromatic hydrocarbon (e.g., toluene) or the reaction may be carried out neat. For toluene and diethyl ether, reaction conditions were preferably 0.75 to 5 mol/liter PO/solvent,  $[PO]/[catalyst] = 250:1$  to  $750:1$  and temperature ranging from 0 to 50 °C. When the reaction was carried out neat, the

[PO]/[catalyst] was preferably 250:1 to 750:1 and the temperature was preferably 0 to 30 °C. Reaction times were preferably 0.5 to 6 hours and TOF ranges from 50 to 250 hr<sup>-1</sup>. Molecular weights ( $M_n$ ) obtained ranged from 168,000 g/mol to 423,000 g/mol with PDI ranging from 1.4 to 2.5. Meso-dyad content was > 99%. Details of polymerization and results are given in Example IV hereinafter.

We turn now to the method of the fourth embodiment, that is a method for producing isotactic poly(butylene oxide) comprising the step of polymerizing rac-1-butylene oxide (BO) in the presence of an isospecific (isotactic specific) catalyst. Exemplary catalysts are those set forth above. Polymerization conditions are the same as those for rac-PO described above. Polymerization was optimized at 25 °C with [BO] = 5M and [BO]/[(salph) CoOAc] = 500:1. m-Dyad content was greater than 99%. Under the same conditions, rac-1-hexene oxide (HO) on increasing reaction time to 18 hr at 25 °C and proceeding neat, gave 3% yield. This is described in Example IX hereinafter.

We turn now to the fifth embodiment of the invention herein. A novel product is isotactic PPO having m-dyad content greater than 81%, e.g., greater than 90%, e.g., at least 99%, and containing polymerization catalyst residue. The fact that polymerization catalyst residue is present indicates that the isotactic PPO product was not obtained by fractionation since fractionation, conventionally by dissolving atactic PPO with acetone, also extracts the polymerization catalyst. Polymerization catalyst residue is detectable by imine shifts in the <sup>1</sup>H NMR spectrum and <sup>13</sup>C{<sup>1</sup>H} NMR spectrum.

We turn now to the sixth embodiment herein. Another novel product is isotactic PPO having m-dyad content > 81%, e.g., > 90%, e.g., at least 99%, containing no residue indicating fractionation of atactic isotactic PPO admixture, e.g., acetone residue or methanol, i.e., indicating the product removal was not obtained by fractionation as described above.

We turn now to the seventh embodiment herein. Another novel product herein is isotactic PPO having m-dyad content greater than 81%, e.g., > 90%, e.g., at least 99%, and  $M_n$  greater than 150,000 g/mol, e.g., greater than 200,000 g/mol. This is exemplified in Table 1 of Example IV.

We turn now to the eighth embodiment herein. Another novel product herein is isotactic PPO having m-dyad content greater than 81%, e.g., > 90%, e.g., at least 99%, and PDI less than 2.0, e.g., less than 1.75, e.g., less than 1.50, especially with  $M_n$  greater than 150,000 g/mol or 200,000 g/mol. This is exemplified in Table I of Example IV.

We turn now to the ninth embodiment herein. Another novel product herein is isotactic PPO having m-dyad content greater than 81%, e.g., > 90%, e.g., at least 99%, and containing absolutely no atactic PPO since isotactic PPO obtained by fractionation contains at least a trace of atactic PPO. The absence of trace amount or more of atactic PPO is detectable by  $^{13}\text{C}\{^1\text{H}\}$  NMR spectroscopy.

We turn now to the tenth embodiment herein, i.e., to the method of modifying the properties of unfractionated isotactic PPO comprising the step of providing admixture of non-isotactic PPO (e.g., syndiotactic PPO or atactic PPO) with the unfractionated isotactic PPO. This method is carried out to provide from 0.1% to 99.9%, e.g., 5% to 50%, by weight nonisotactic PPO in admixture with from 99.9% to 0.1%, e.g., 95% to 50% isotactic PPO. The method is carried out, for example, to introduce some flexibility. This method is exemplified in Example XI herein.

The term “unfractionated isotactic PPO” is used herein to mean polymer unaltered from its crude state. Unfractionated isotactic PPO is shown by detection of presence of polymerization catalyst residue, no detection of solvent that fractionates isotactic PPO from atactic isotactic admixture and by detection of at least trace amount of atactic PPO.

The invention is illustrated by the following working examples.

**Example I**  
**Preparation of (salph) Co**

***N,N'-bis-(3,5-di-*tert*-butylsalicylidene)-1,2-phenylenediaminocobalt (1).***

Under nitrogen, degassed ethanol (150 mL) was added to a flask charged with a Teflon-coated stir bar, *N,N'*-bis-(3,5-di-*tert*-butylsalicylidene)-1,2-phenylenediamine (3.0 g, 5.5 mmol) and cobalt(II) acetate tetrahydrate (0.98 g, 3.9 mmol). The flask was

heated to 80 °C for 20 minutes and then cooled to 22 °C. Solvent was removed by vacuum filtration in air and solids were washed with methanol. The dark red powder was recrystallized by dissolving it in methylene chloride (30 mL) and layering with hexanes (700 mL), followed by cooling to 0 °C. After 24 h, dark red crystals of **1** were obtained and isolated by vacuum filtration (2.3 g, 98% yield). IR (KBr cm<sup>-1</sup>): 2960, 2873, 1575, 1523, 1465-1359, 1260. Crystallographic data (solid state structure, shown below): triclinic,  $a = 9.2149(3)$  Å,  $b = 12.9485(5)$  Å,  $c = 14.3796(6)$  Å,  $\alpha = 107.645(2)^\circ$ ,  $\beta = 93.624(2)^\circ$ ,  $\gamma = 95.851(2)^\circ$ ,  $V = 1618.5(1)$  Å<sup>3</sup>, space group P-1;  $Z = 2$ , formula weight 597.68 g/mol for (C<sub>36</sub>H<sub>46</sub>CoN<sub>2</sub>O<sub>2</sub>) and density (calc.) = 1.226 mg/m<sup>3</sup>;  $R1 = 0.0326$  and  $Rw2 = 0.0945$  ( $I > 2\sigma (I)$ ).

**Example II**  
**Preparation of (salph) Co OAc**

**(*N,N'*-bis-(3,5-di-*tert*-butylsalicylidene)-1,2-phenylenediaminocobalt acetate (2).** To a 200 mL beaker charged with a Teflon stirbar, **1** (1.00 g, 1.67 mmol) dissolved in methylene chloride (10 mL), and acetic acid (0.100 mL, 1.75 mmol) was added and the solution stirred open to air while solvent was allowed to evaporate, yielding a bright red powder. The powder, **2**, was washed with pentane and dried *in vacuo* for 12 h (1.1 g, 97% yield). IR (KBr cm<sup>-1</sup>): 2967, 2876, 1613, 1580, 1524, 1490-1361, 1252.

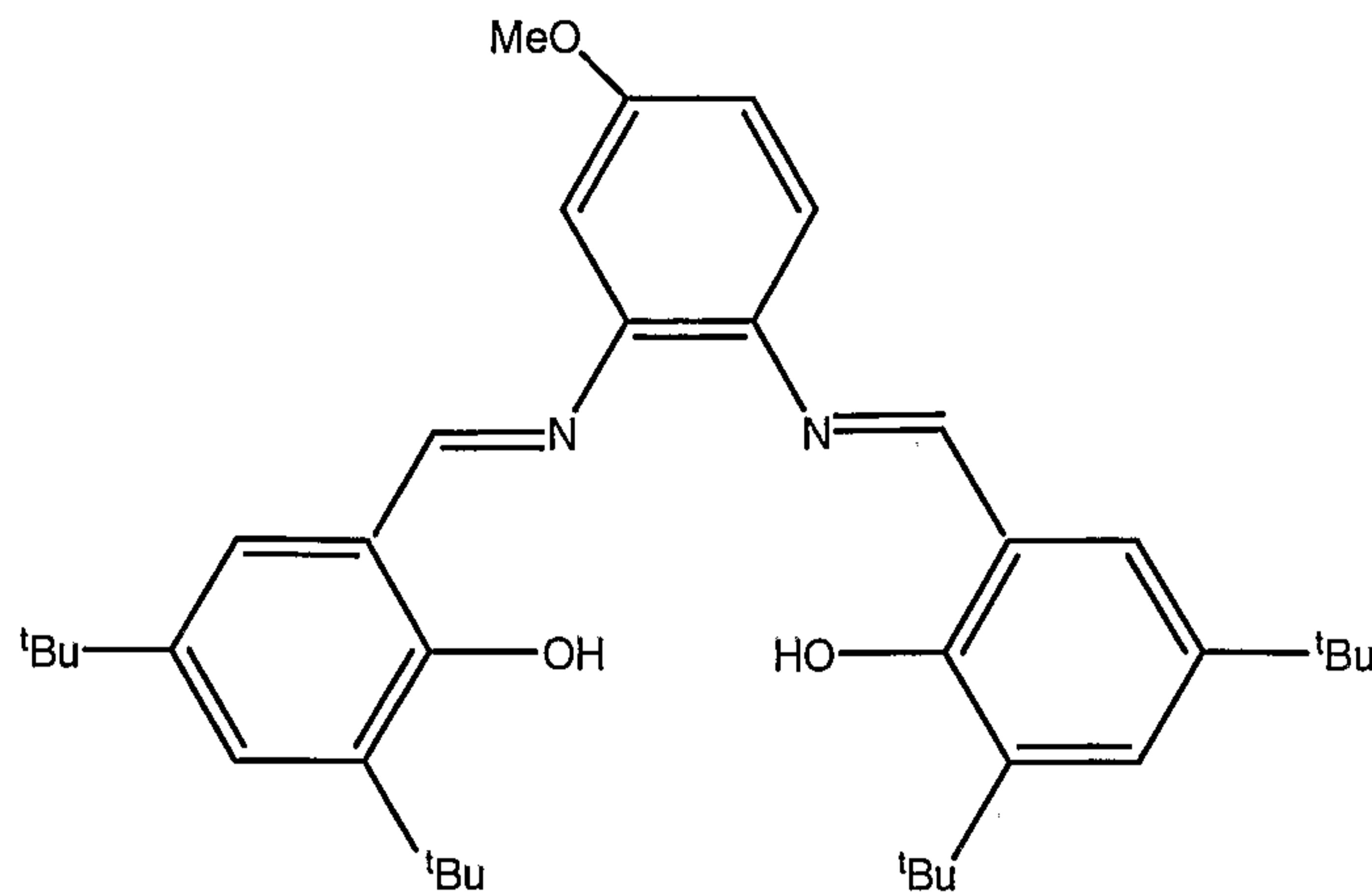
To make (salph) CoBzOAc, an equimolar amount of benzylacetic acid is substituted for the acetic acid.

To make (salph) CoNpOAc, an equimolar amount of naphthylacetic acid is substituted for the acetic acid.

To make (salph) CoOMe, an excess amount of methanol is substituted for the acetic acid and dissolution in methanol is substituted for dissolution in methylene chloride.

**Example III**  
**Preparation of (methoxy salph) Co OAc**

Compound 3 is depicted below.



3

Compound 3 was prepared as set forth below.

**Preparation of 3:**

In a 100 mL round bottom flask equipped with Teflon stirbar, 3,5-di-*tert*-butyl-2-hydroxybenzaldehyde (1.47 g, 6.27 mmol) was added to 4-methoxy-1,2-phenylenediamine (0.433 g, 3.14 mmol) dissolved in THF (10 mL). Ethanol (40 mL) was added and the solution stirred at 24 °C. A reflux condenser was then attached to the flask and it was heated to 95 °C for 18 h. The reaction was allowed to cool to 24 °C. The solution was concentrated to 20 mL, causing solids to precipitate. Solids were filtered and washed with cold ethanol to give a yellow/orange solid (0.424 g, 23.7 %).

Compound 3 was converted to (methoxy salph) Co, Compound 4, as follows:

**Preparation of 4:**

3 (0.400 g, 0.701 mmol) and cobalt acetate tetrahydrate (0.124 g, 0.498 mmol) were combined in a 50 mL round bottom flask. Under N<sub>2</sub>, degassed ethanol was added and stirred at 24 °C for 2 h. The mixture was filtered under N<sub>2</sub> and washed with H<sub>2</sub>O (15 mL) followed by MeOH (15 mL). The solids were collected and dried under vacuum for several hours to give a dark red/brown powder (0.289 g, 95.4 %).

Compound 4 was converted to (methoxy salph) Co OAc (compound 5) as follows:

**Preparation of 5:**

**4** (0.2 g, 0.4 mmol) was dissolved in dry  $\text{CH}_2\text{Cl}_2$  (30 mL) under  $\text{N}_2$  and stirred for 5 min. before acetic acid (0.05 mL, 0.9 mmol) was added. The solution stirred for an additional 5 min. before the flask was opened to air. The solution stirred open to air for 18 h while solvent evaporated. The solids were dried under vacuum for 18 h, then washed with pentane and dried under vacuum to give a dark red powder (0.2 g, 80 %).

**Example IV**  
**Polymerization of rac-PO to Produce Isotactic PPO**

The following procedures were utilized to polymerize rac-PO using (salph) Co OAc(**2**).

**Representative Procedure for Polymerization of rac-PO.** In a drybox, a Schlenk tube was charged with **2** (9.4 mg, 0.014 mmol) and a Teflon stirbar, then sealed and removed from the drybox. Toluene (6.6 mL) was added under  $\text{N}_2$  and the solution was brought to 0 °C. rac-PO (0.50 mL, 7.2 mmol) was added via air-tight syringe, and was stirred for 2 h at 0 °C. An aliquot was taken from the reaction mixture for NMR analysis before it was quenched with 1N HCl (5.0 mL). Unreacted PO was removed *in vacuo*, and methylene chloride (20 mL) was added to dissolve precipitated polymer. The organic layer was separated and solvent was removed by rotary evaporation at 22 °C (370 mg, 89%). At this stage the polymer contains catalyst residue. Polymer was purified by dissolving in hot acetone (5.0 mL) then adding the resulting solution dropwise to acetone (150 mL) at 25 °C. The polymer solution was cooled to 0 °C for 3 h. White precipitate was filtered and dried *in vacuo* to constant weight (360 mg, 86%).

**Polymerization of rac-PO at 40°C.** A Schlenk tube was prepared in a drybox and solvent was added according to the above representative procedure. rac-PO (0.50 mL, 7.2 mmol) was added via air-tight syringe. The Schlenk tube was sealed and immediately heated to 40 °C. The polymerization mixture stirred for 2 h, then was quickly cooled by immersing the Schlenk tube in cold water (100 mg, 32%).

Results and conditions are set forth in Table 1 below.

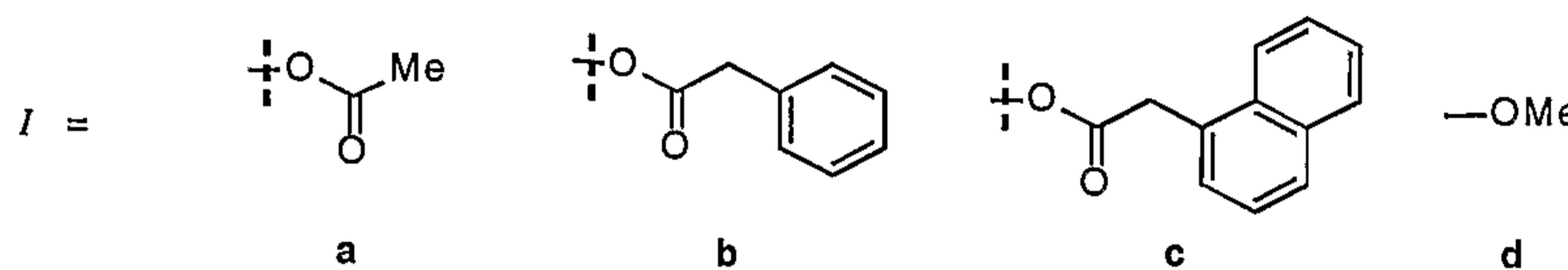
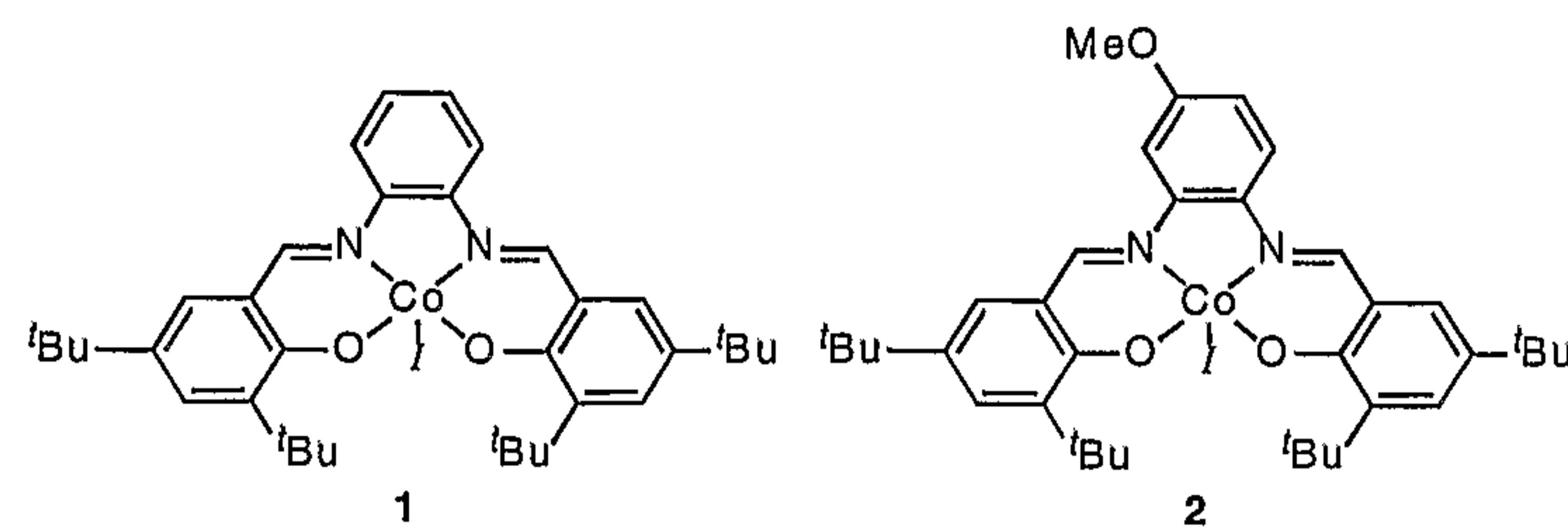
**Table 1<sup>a</sup>**  
**Isospecific Polymerization of rac-Propylene**  
**Oxide catalyzed by (Salph) Co OAc**

Entry	solvent	[PO] (mol/L)	[PO]/[2]	T <sub>rxn</sub> (°C)	yield <sup>b</sup> (%)	TOF <sup>c</sup> (h <sup>-1</sup> )	M <sub>n</sub> <sup>d</sup> (kg/mol)	M <sub>w</sub> /M <sub>n</sub> <sup>d</sup>	mm-triads <sup>e</sup> (%)	T <sub>m</sub> <sup>f</sup> (°C)
1	THF	1.0	500	0	<1	ND	ND	ND	ND	ND
2	CH <sub>2</sub> -Cl <sub>2</sub>	1.0	500	0	<1	ND	ND	ND	ND	ND
3	Toluene	1.0	500	0	23	60	168	1.45	>99	67
4	Toluene	1.0	500	0	89	220	287	1.40	>99	66
5	Toluene	0.5	500	0	1	3	ND	ND	ND	ND
6 <sup>g</sup>	Toluene	1.0	1000	0	6	30	144	4.81	>99	67
7	Toluene	1.0	500	25	40	100	222	2.46	>99	68
8	Toluene	1.0	500	40	32	80	209	2.11	<99	67
9	Toluene	1.0	500	-20	<1	ND	ND	ND	ND	ND

<sup>a</sup> Polymerization run with 0.5 mL of rac-propylene oxide (rac-PO) for 2 hr (applies to all entries but entry 6). <sup>b</sup> Based on crude polymer weight. <sup>c</sup> Turnover frequency = mol PO/(mol 2 · h). <sup>d</sup> Determined by size exclusion chromatography calibrated by polystyrene standards in 1,2,4-trichlorobenzene at 140°C. <sup>e</sup> Determined by <sup>13</sup>C{<sup>1</sup>H} NMR spectroscopy (CDCl<sub>3</sub>, 125 MHz). <sup>f</sup> Determined by differential scanning calorimetry, run from -90 to 90 °C at 1 °C/min. <sup>g</sup> 1.0 mL of rac-PO.

Isospecific polymerization of rac-PO was carried out utilizing (salph) CoOAc (1a in Table 2 below), (salph) CoBzOAc (1b in Table 2 below), (salph) CoNpOAc (1a in Table 2 below), (salph) CoOMe (1d in Table 2 below) and (methoxy salph) CoOAc with results as shown in Table 2 below.

**Table 2**  
**Isospecific Polymerization of rac-PO Using (salph) Co OAc, (salph) Co Bz OAc,**  
**(salph) Co Np OAc, (salph) Co OMe and (methoxy salph) Co OAc**



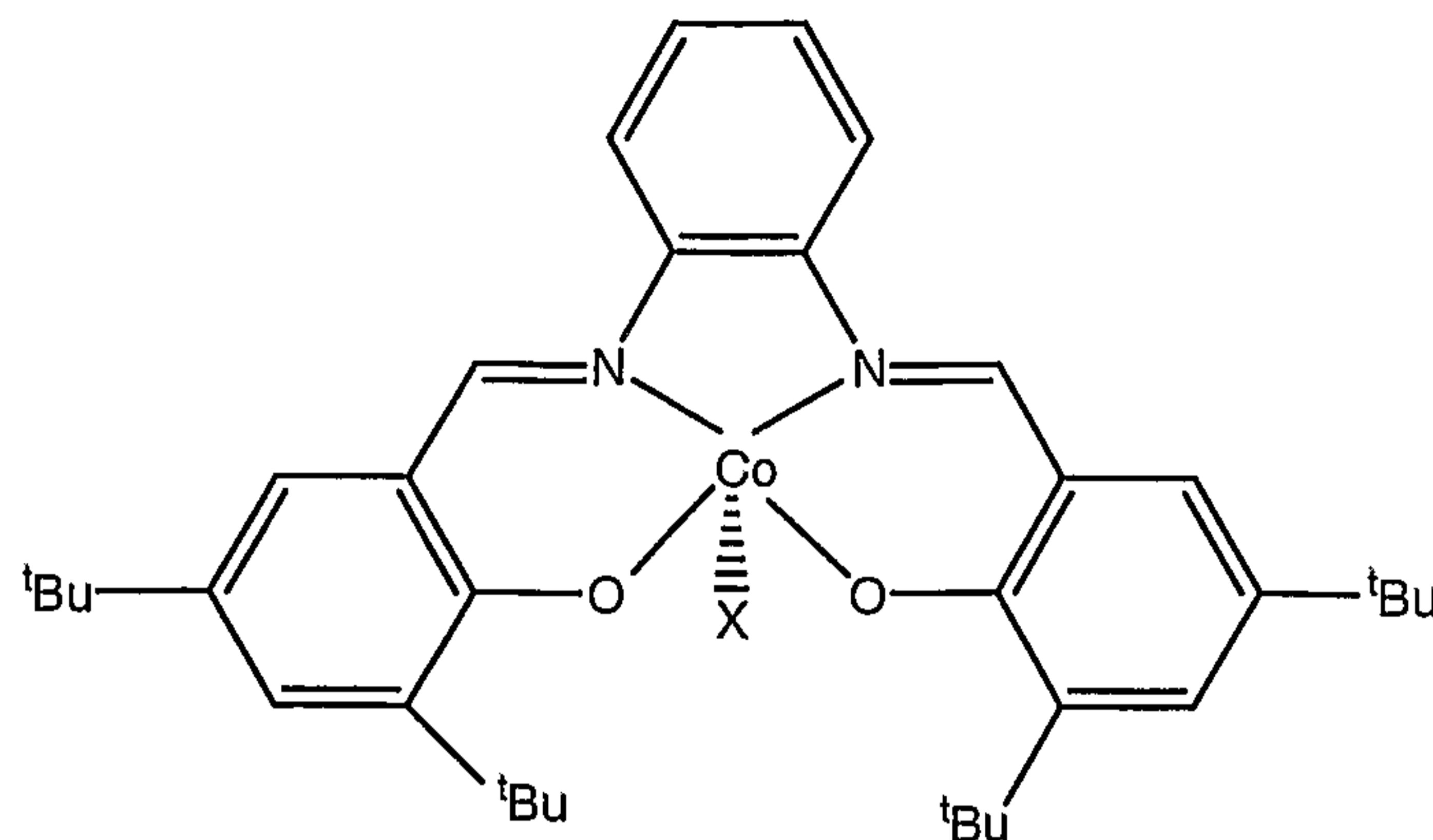
Run	Initiator	[PO]/[Co]	Solvent	[PO] mol/L	Temp. (°C)	Time (h)	Yield <sup>a</sup> (%)	<i>M<sub>n</sub></i>	<i>M<sub>w</sub>/M<sub>n</sub></i>	[mm] (%)	<i>T<sub>m</sub></i> (°C)	Exp. N.o.
1	1a	500	toluene	1.0	0	2	86	287	1.4	> 99	64	HMA2-103
2	1b	500	toluene	5.0	0	4	86	423	1.4	> 99	67	HMA3-021
3	1c	1000	—	neat	25	20	6 <sup>b</sup>	294	1.4	99	65	HMA3-103
4	1d	500	—	neat	25	4	72	371	1.5	99	69	HMA4-115
5	2a	500	—	neat	25	18	32	492	1.6	> 99	( )	KLP2-196

<sup>a</sup> Isolated yield from 0 °C acetone. <sup>b</sup> Determined by crude weight.

In all these experiments, no trace of atactic PPO is detectable by <sup>13</sup>C {<sup>1</sup>H} NMR spectroscopy method of analysis in the isotactic PPO product.

**Example V**  
**Polymerization of rac-PO With Catalyst Where Salph Includes**  
**di-tert butyl, and Initiating Ligand is Varied**

The Catalyst used has the structural formula



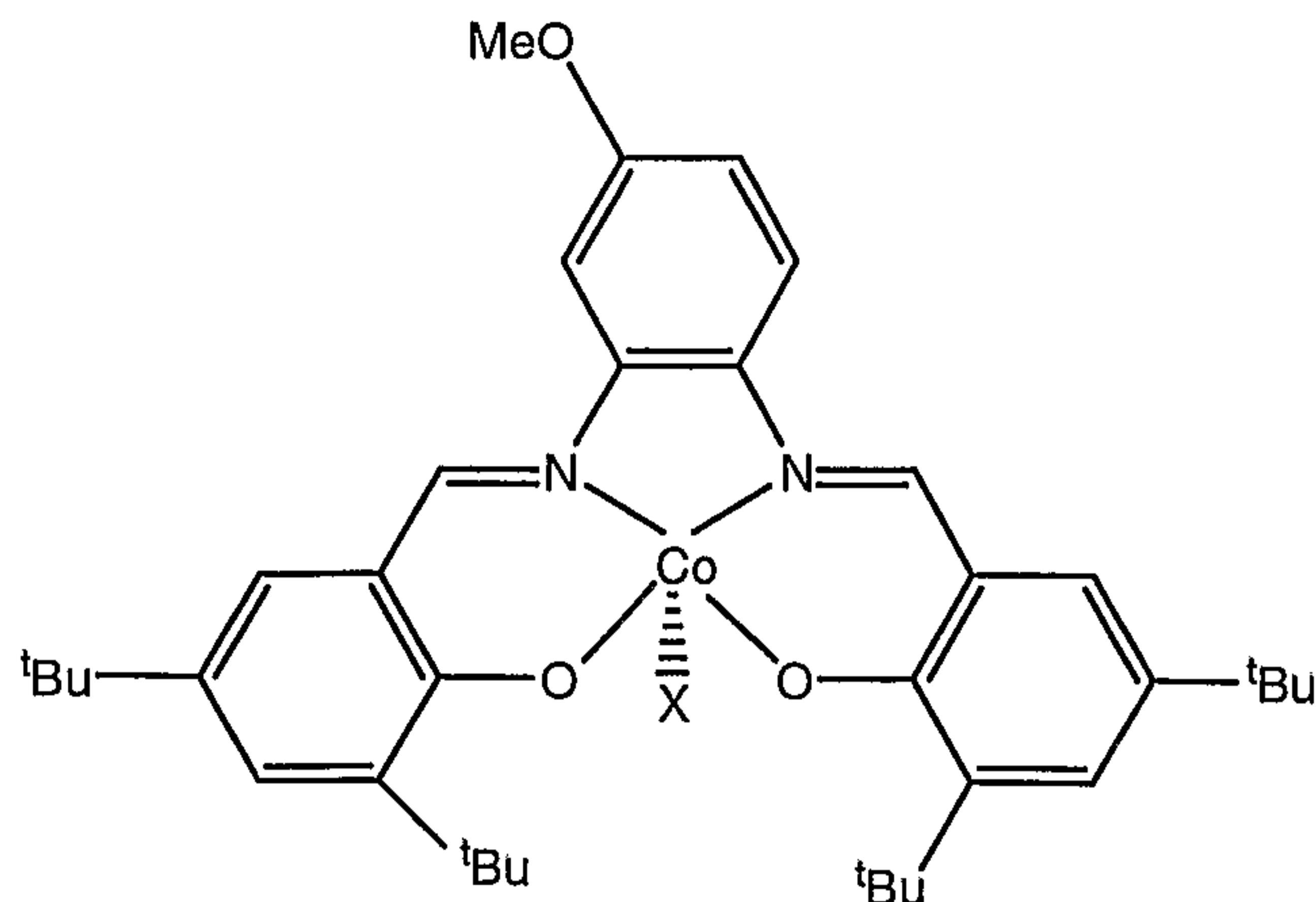
Runs were carried out with reaction conditions and yield results as set forth in Table 3 below. Polymerizations were either neat or run in toluene. In all cases, mm-triad was greater than 99%.

Table 3

Entry	X	Time h	[PO] [Co]	Temp °C	[PO] M	Yield
klp-5-7	Br	18	500	25	7	15.5
klp-2-234	OCH <sub>3</sub>	18	500	25	14	89.2
klp-2-287	malonic acid	20	500	25	2	6.7
klp-2-282	citric acid	20	500	25	14	3
klp-2-283	pimelic acid	20	500	25	14	5
klp-2-293	glutaric acid	20	500	25	14	2.5
klp-3-41	Ad-COOH	24	500	25	14	37 (1-adamantyl carboxylic acid)
klp-4-147	Cl	18	500	25	7	18
klp-5-79	OH	18	500	25	14	88.2

Example VI  
Polymerization of rac-PO With Catalyst Where Methoxysalp Includes  
di-tert butyl and Initiating Ligand is Varied

The catalyst has the structural formula:



Runs were carried out with reaction conditions and yield results as set forth in Table 4 below. All reactions were run neat and mm-triad were greater than 99%.

Table 4

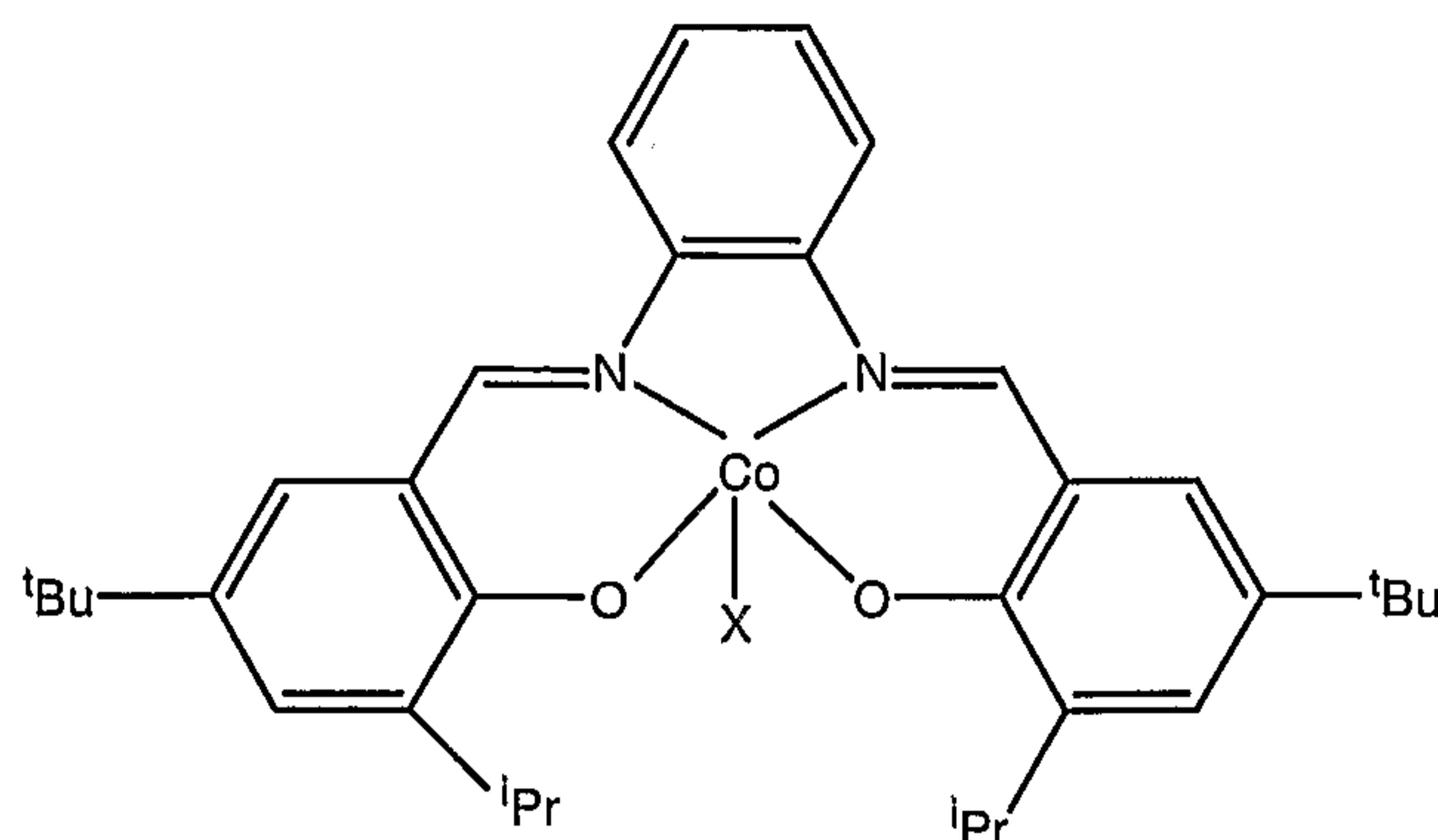
Entry	X	Time h	PO:Co	Temp(°C)	[PO] M	yield (%)
klp-2-175	OAc	18	0.2	25	14	78.8
klp-2-206	4-CF <sub>3</sub> -benzoic acid	18	500	25	14	1
klp-5-81	OMe	18	500	25	14	17.1

Example VII

Polymerization of rac-PO With Catalyst Where Salph

Includes 3-*tert*-butyl-5-Isopropyl and X is OMe

The catalyst has the structural formula:



where X is OMe.

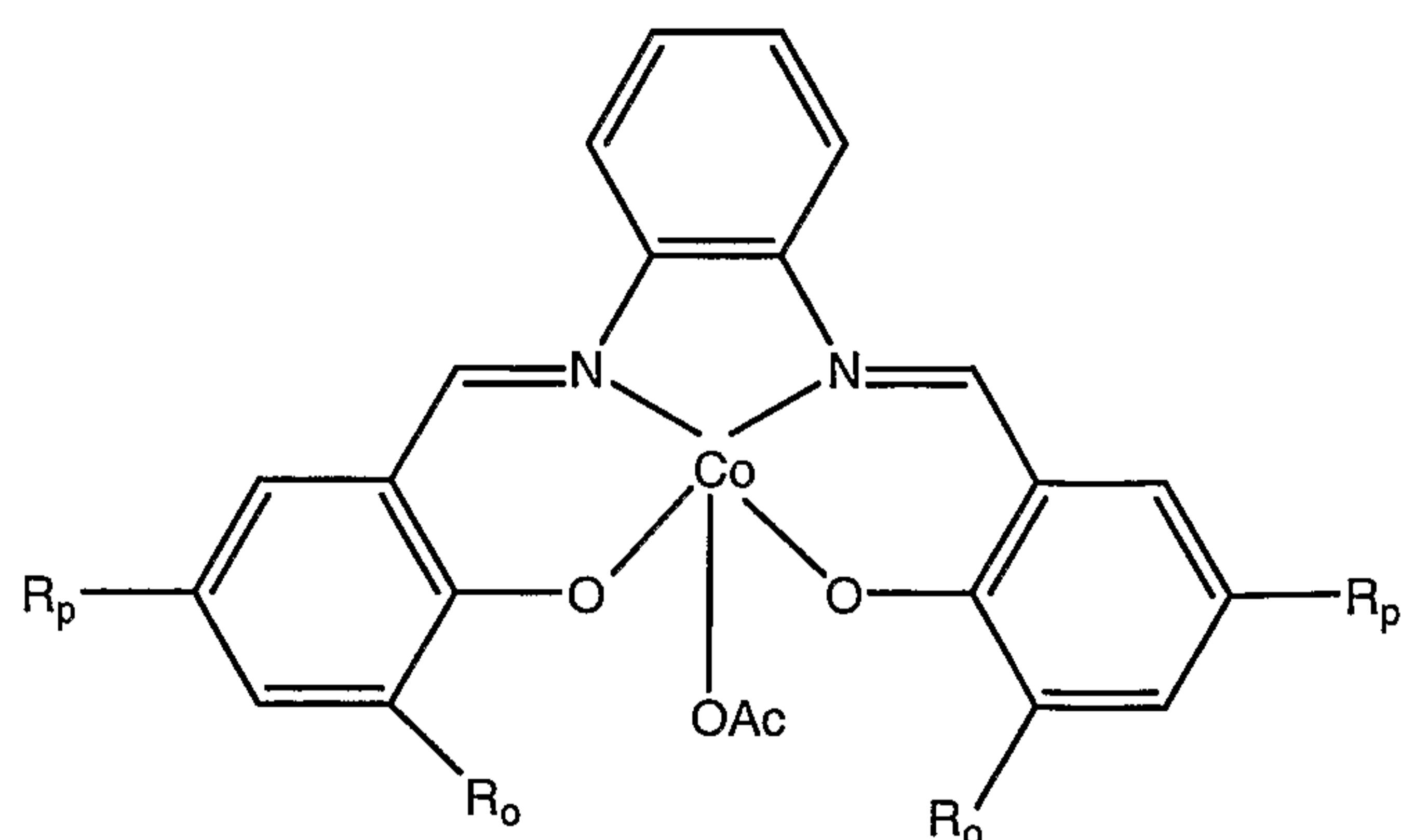
Runs were carried out with [PO]:[Co] being 500:1 and [PO] being 7M in toluene with other conditions and results set forth in Table 5 below.

**Table 5**

Entry	Time H	Temp °C	Yield %	[mm] %	[mr] %	[rr]
klp-4-117	19	25	14.8	76.3	17.0	6.7
klp-5-71	18	25	10.5	73.4	16.5	10.1

**Example VIII**  
**Polymerization of rac-PO Where Alkyl Substituents**  
**On Salicylidine Are Varied and X is OAc**

The catalyst has the Structural Formula:



Polymerization conditions and yield results are given in Table 6 below.

**Table 6**

Entry	Ro	Rp	Solvent	[PO] (M)	PO:Co	Time (h)	Temp (°C)	Yield (%)	m-dyad (%)
klp-4-72	iPropyl	tButyl	toluene	3	500	17	25	20.3	86
klp-4-31	Ethyl	tButyl	hexanes	5	500	24	25	5.4	72
klp-3-281	Methyl	tButyl	-	14	500	24	25	14.2	65

**Example IX****Polymerization of rac-1-Butylene Oxide Using 2 Which is (salph) Co OAc**

**Optimized Polymerization of rac-1-butylene oxide (BO).** A vial was charged with **2** (7.5 mg, 0.011 mmol), Teflon stirbar and toluene (0.65 mL) in a drybox. While the mixture was stirring, rac-BO (0.50 mL, 5.8 mmol) was added to the vial. The vial was immediately sealed with a Teflon-lined cap and brought out of the drybox. The reaction was allowed to stir at 25 °C for 4 h then was quenched with 1N HCl. Methylene chloride (20 mL) was added to the solution and the organic layer was separated. Solvent was removed by rotary evaporation at 22 °C. To remove remaining cobalt, polymer was dissolved in toluene (40 mL) and stirred with activated alumina before filtering by vacuum filtration. Solvent was removed from the filtrate by rotary evaporation at 22 °C, followed by drying *in vacuo* to give a pale yellow gel (110 mg, 26%).  $^1\text{H}$  NMR ( $\text{CDCl}_3$ , 500 MHz):  $\delta$  0.94 (broad, 3H), 1.51-1.58 (broad, 2H), 3.33 (broad, 1H), 3.55 (broad, 2H).  $^{13}\text{C}\{\text{H}\}$  NMR ( $\text{CDCl}_3$ , 125 MHz):  $\delta$  9.92, 25.07, 72.62, 81.11. GPC data:  $M_n = 185,000$  g/mol,  $M_w/M_n = 2.08$ .

**Example X****Polymerization of 1-Hexene Oxide Using (salph) Co OAc**

**Polymerization of 1-hexene oxide (HO).** In the drybox, **2** (6.6 mg, 0.012 mmol) was added to a vial charged with a Teflon stir bar. While stirring, HO (0.50 mL, 4.1 mmol) was added to the vial. The vial was immediately sealed with a Teflon-lined cap and brought out of the drybox. The reaction stirred at 25 °C for 18 h, then an aliquot of the resultant polymerization mixture was removed from the vial for <sup>1</sup>H NMR analysis (3.0%).

#### Example XI

#### Producing Mixture of Unfractionated Isotactic PPO and Non-isotactic PPO

**Preparation of (N,N'-bis-(5-tert-butyl-3-isopropylsalicylidene)-1,2-phenylenediamino)cobalt acetate (6).** In a drybox, a schlenk tube was charged with AlCl<sub>3</sub> (1.5 g, 11.2 mmol) and Teflon coated stirbar. Under N<sub>2</sub>, 2-isopropylphenol (15.1 mL, 112 mmol) was added followed by 2-chloro-2-methylpropane (14.5 mL, 134 mmol). The resulting mixture stirred at 25 °C 18 h. Ice water and diethyl ether were added. The ether layer was washed twice with H<sub>2</sub>O then once with brine. The organic layer was dried over MgSO<sub>4</sub>. The crude product was purified by column chromatography (20% EtOAc/hexanes) to give a yellow oil (19 g, 87%). The purified phenol (12 g, 62 mmol) was dissolved in dry toluene and 2,6-lutidine (12 mL, 100 mmol). The solution was cooled to 0 °C and SnCl<sub>4</sub> was added slowly. The reaction stirred for 15 min. before paraformaldehyde was added. A drying tube was attached to the schlenk tube, which was then heated to 100°C for 16 h. The reaction cooled to 25 °C before adding 1N HCl and filtering the resulting suspension over celite. The organic layer was washed with H<sub>2</sub>O and dried over MgSO<sub>4</sub>. Concentration yielded a viscous yellow/brown oil (10 g, 74%). The oil was dissolved in MeOH (75 mL) and

1,2-diaminobenzene (2.4 g, 23 mmol) was added. The solution refluxed for 4 h, then was cooled to 25 °C. Yellow solids crashed out and were filtered, washed with MeOH, and dried under vacuum (4.0 g, 34%). The resulting ligand (1.5 g, 2.9 mmol), was dissolved in toluene (15 mL) and cobalt acetate tetrahydrate (.73 g, 2.9 mmol) was dissolved in MeOH. The toluene solution was added to the MeOH solution and the solution stirred at 25 °C for 1 h. Red solids were filtered, washed with MeOH and dried under vacuum (1.4 g, 83%). The solids were dissolved in CH<sub>2</sub>Cl<sub>2</sub> and acetic acid (0.10 mL, 2.4 mmol) was added. The solution stirred open to air until all solvent had evaporated. The solids were washed with pentane and dried under vacuum (1.4 g, 93%).

**Representative polymerization of *rac*-PO with 6:**

In a drybox, a vial was charged with **6** (9.0 mg, .014 mmol) and a Teflon stirbar. Toluene (0.50 mL) was added and the suspension stirred 3 min. *rac*-PO (0.50 mL, 7.1 mmol) was then added and the vial was quickly sealed with a Teflon-lined cap. The polymerization stirred at 25 °C for 20 h. The polymerization was quenched with 1N HCl and remaining PO was removed under vacuum. The polymer residue was dissolved in CH<sub>2</sub>Cl<sub>2</sub> and the HCl was allowed to react overnight. The solution was washed with H<sub>2</sub>O, dried over Na<sub>2</sub>SO<sub>4</sub>, then concentrated under vacuum (.063 g, 15%). The resulting polymer had a m-dyad of 84% by <sup>13</sup>C{<sup>1</sup>H} NMR spectroscopy, and therefore, acts as a mixture of roughly 20% atactic PPO and 80% isotactic PPO.

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Variations

The foregoing description of the invention has been presented describing certain operable and preferred embodiments. It is not intended that the invention should be so limited since variations and modifications thereof will be obvious to those skilled in the art, all of which are within the scope of the invention.

**WE CLAIM:**

1. An isospecific catalyst for the polymerization of epoxides to poly(alkyleneoxides), said catalyst comprising Co(III) and a Schiff base.
2. The isospecific catalyst of claim 1, wherein the Co(III)-containing species comprises salph-Co-(initiating ligand).
3. The isospecific catalyst of claims 1 or 2, wherein admixture of the catalyst with at least one of a solvent and an epoxide, provides a catalytic complex containing a plurality of cobalt centers.
4. The isospecific catalyst of claim 3, wherein the admixture comprises a chiral catalyst environment due to aggregation of the salph-Co-(initiating ligand).
5. The isospecific catalyst of any one of claims 2 through 4, wherein the initiating ligand is selected from the group consisting of:
  - a. a halide;
  - b. cyano;
  - c. azide;
  - d. hydroxide;
  - e. C<sub>1</sub>-C<sub>20</sub> amido;
  - f. C<sub>1</sub>-C<sub>20</sub> carboxylate;
  - g. C<sub>2</sub>-C<sub>20</sub> dicarboxylate;
  - h. C<sub>4</sub>-C<sub>20</sub> tricarboxylate;
  - i. C<sub>5</sub>-C<sub>20</sub> aryl carboxylate;

- j. C<sub>1</sub>-C<sub>20</sub> alkoxide;
- k. a phenoxide; and
- l. a combination of any two or more of (a) through (k);

wherein any of the initiating ligands (f)-(i) containing two or more carbons may be optionally substituted by a hydroxyl group.

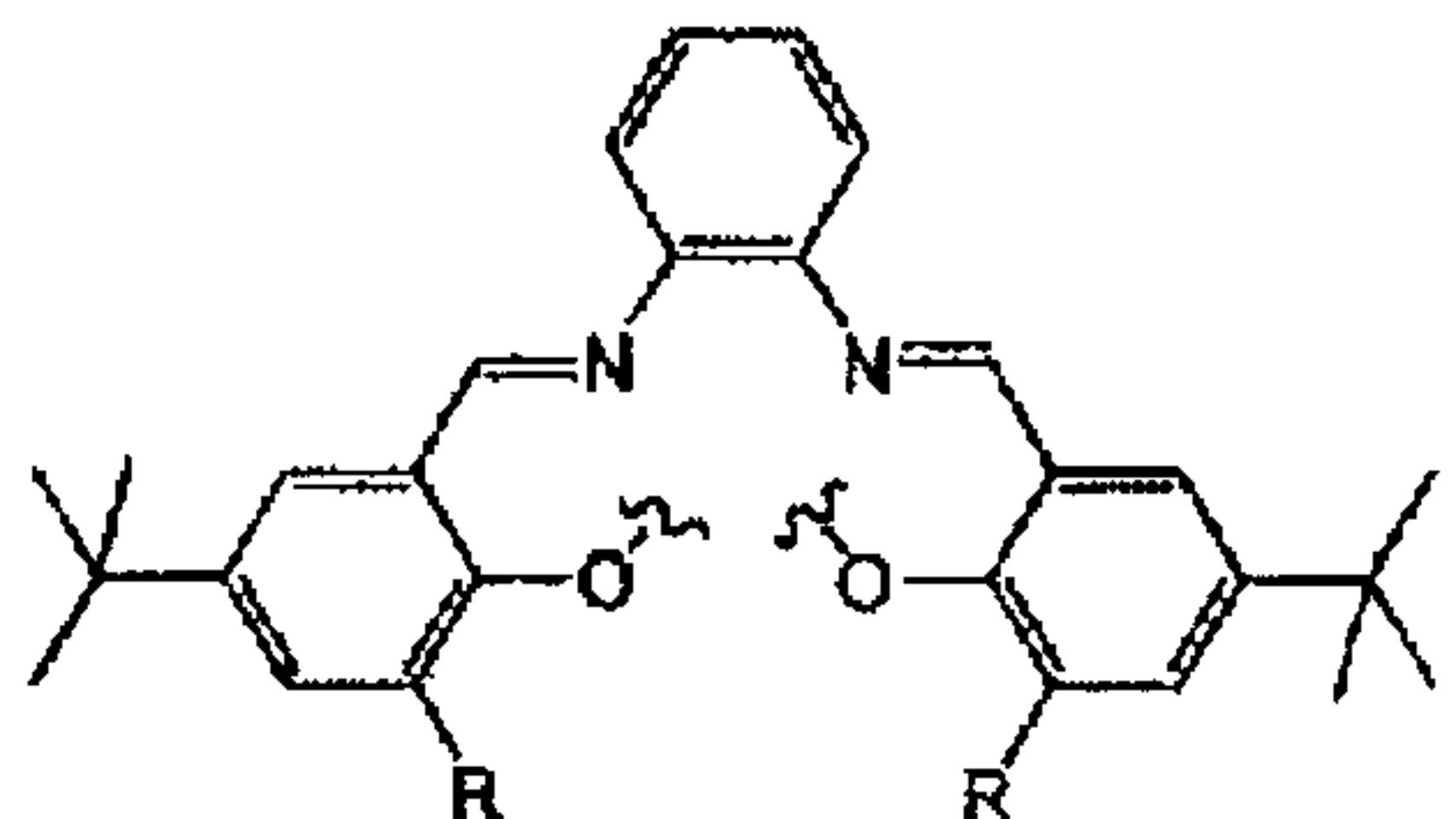
6. The isospecific catalyst of any one of claims 2 through 5, wherein salph has the formula:

wherein each of R<sup>3</sup> and R<sup>4</sup> is independently selected from -OMe, and -H, and each of R<sup>1</sup> and R<sup>2</sup> is independently selected from the group consisting of:

- a. methyl;
- b. ethyl;
- c. isopropyl; and
- d. tertiary butyl.

7. A method of producing isotactic poly(alkyleneoxide), comprising the step of contacting an alkyl epoxide with an isospecific catalyst, said catalyst comprising Co(III) and a Schiff base, and wherein an m-dyad content of the polymer in its crude state exceeds 81% prior to any optional fractionations.

8. The method of claim 7, wherein the alkyl epoxide is a C<sub>3</sub>-C<sub>6</sub> epoxide.
9. The method of claim 7, wherein the isospecific catalyst comprises any of the catalysts of any one of claims 1 through 6.
10. A method for producing unfractionated isotactic poly(C<sub>3</sub>-C<sub>10</sub> alkyleneoxide) having an m-dyad content greater than 81% comprising the step of: homopolymerizing a C<sub>3</sub>-C<sub>10</sub> alkyl epoxide in the presence of an isospecific catalyst, said catalyst comprising Co(III) and a Schiff base.
11. The method of claim 10, wherein fractionation is not required to achieve the stated m-dyad content.
12. The method of claim 11, wherein the isospecific catalyst is selected from the group consisting of:
  - a. salph-Co-(initiating ligand);
  - b. methoxy salph-Co-(initiating ligand);and a combination of (a) and (b).
13. The method of claim 12, wherein salph has the formula:



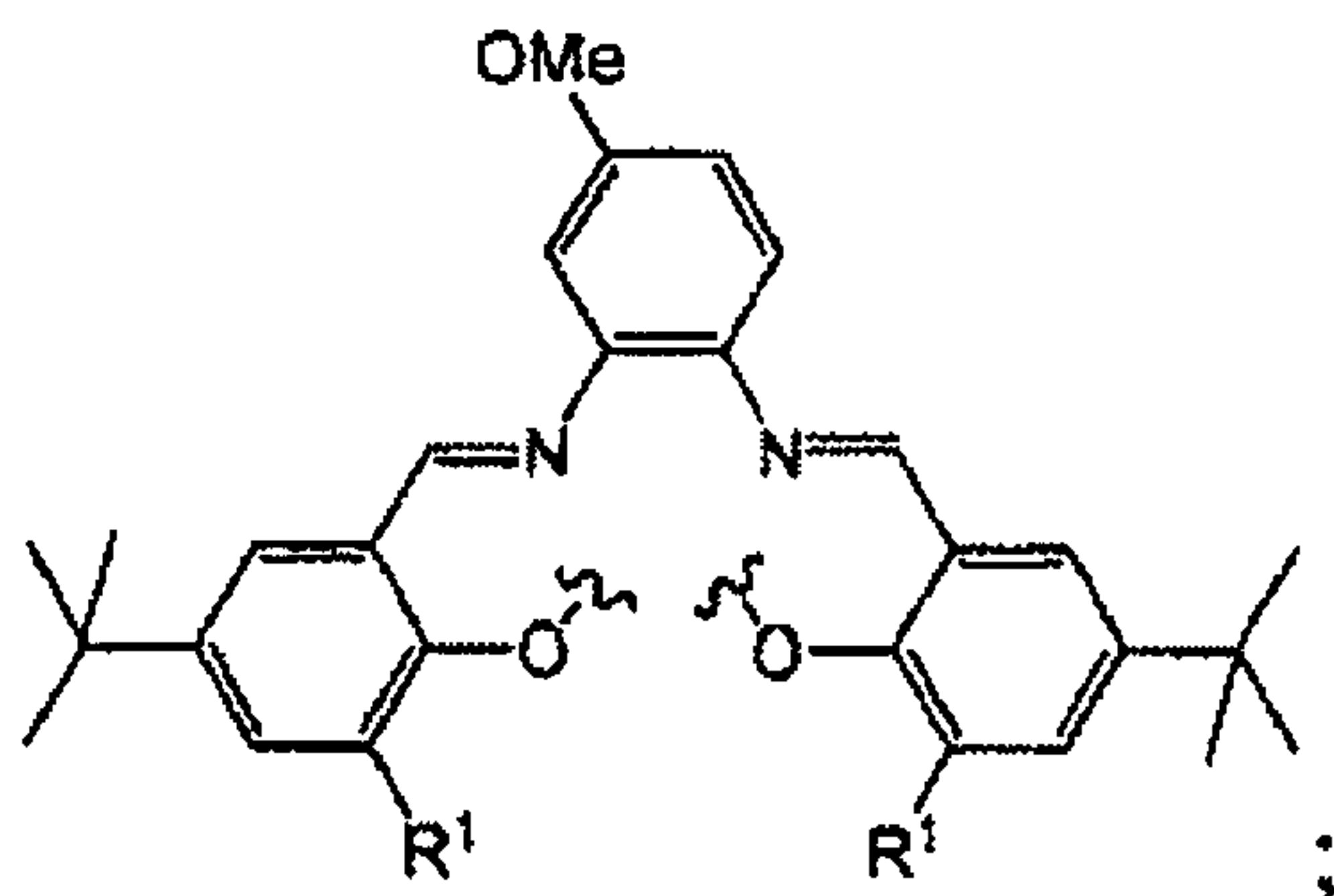
where R is selected from the group consisting of:

- a. methyl;
- b. ethyl;

c. isopropyl; and

d. tertiary butyl.

14. The method of claim 10, wherein methoxy salph has the formula:



where  $R^1$  is selected from the group consisting of:

a. methyl;

b. ethyl;

c. isopropyl; and

d. tertiary butyl.

15. The method of claim 12, wherein the initiating ligand is selected from the group consisting of:

a. halide;

b. cyano;

c. azide;

d. hydroxide;

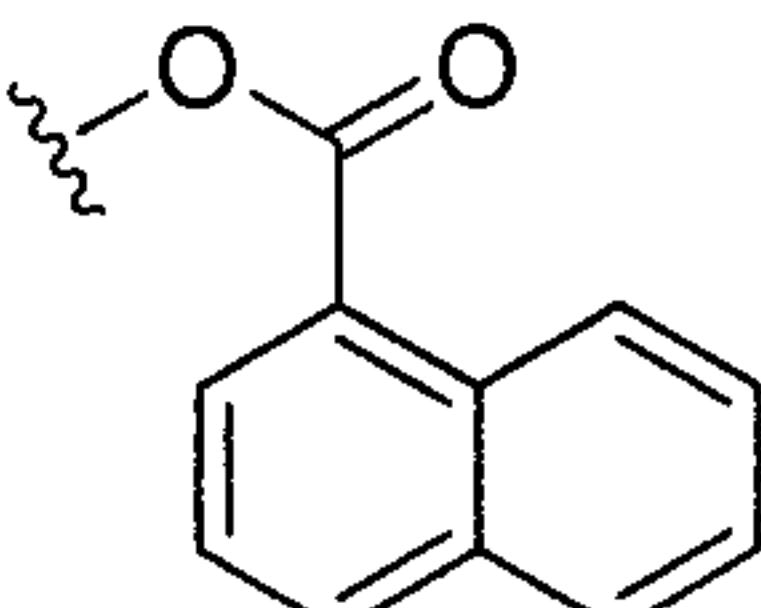
e.  $C_0$ - $C_{20}$  amido;

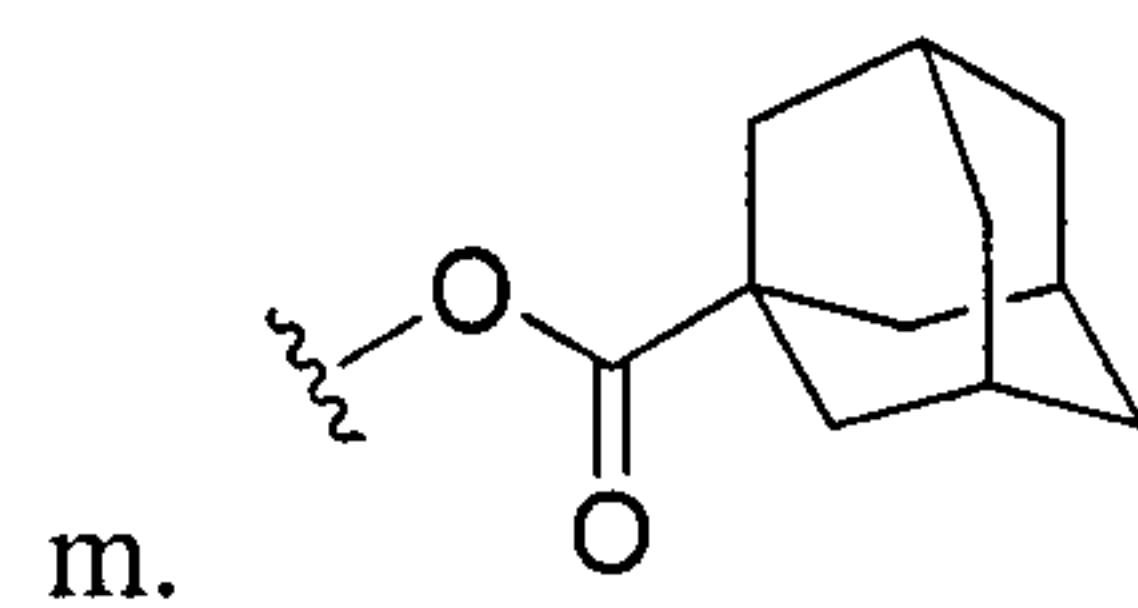
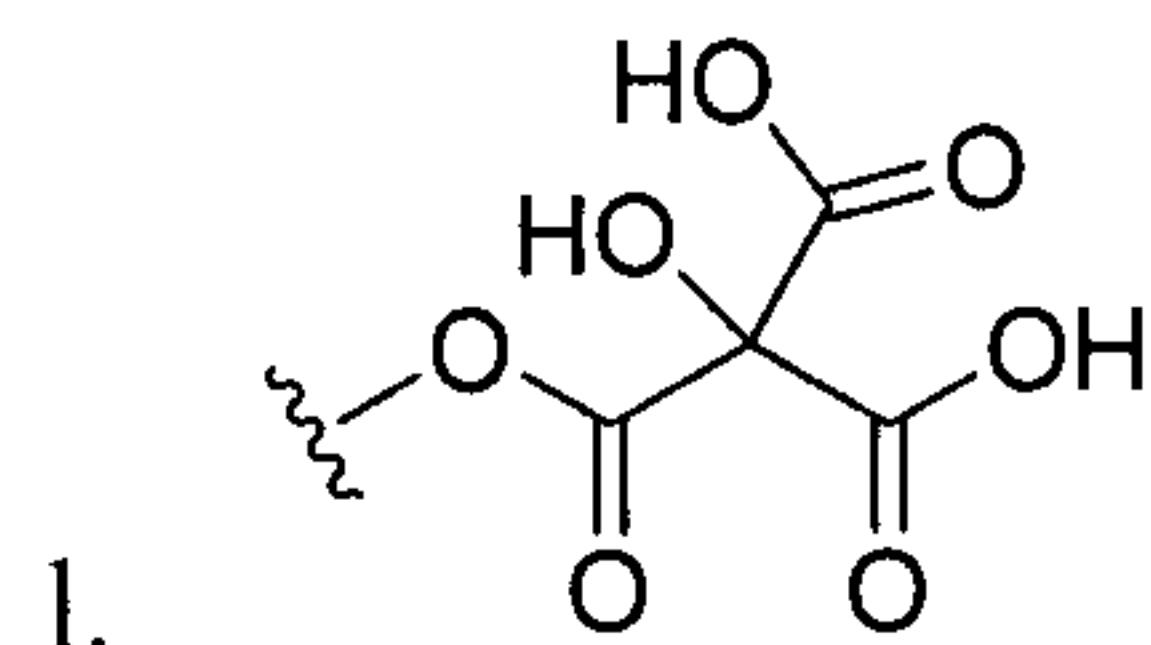
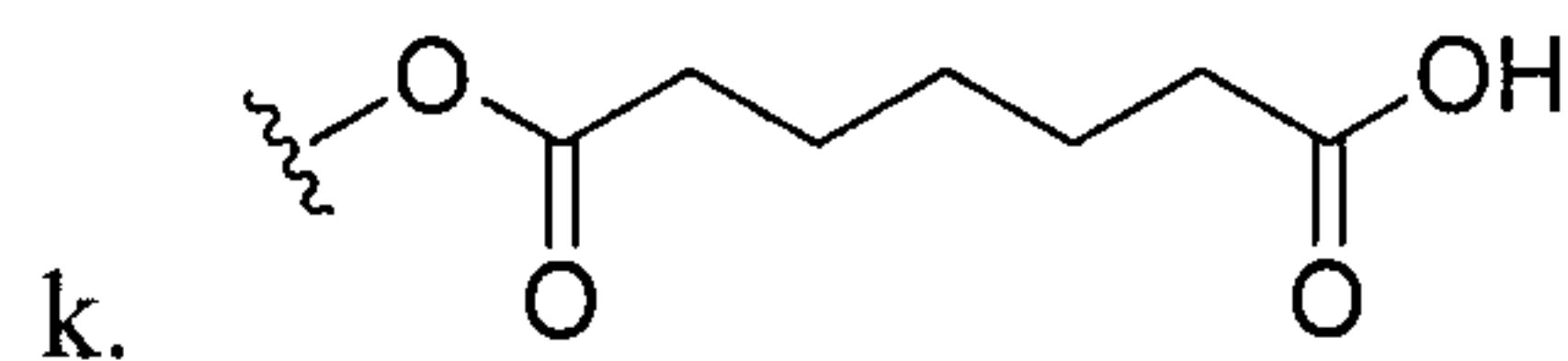
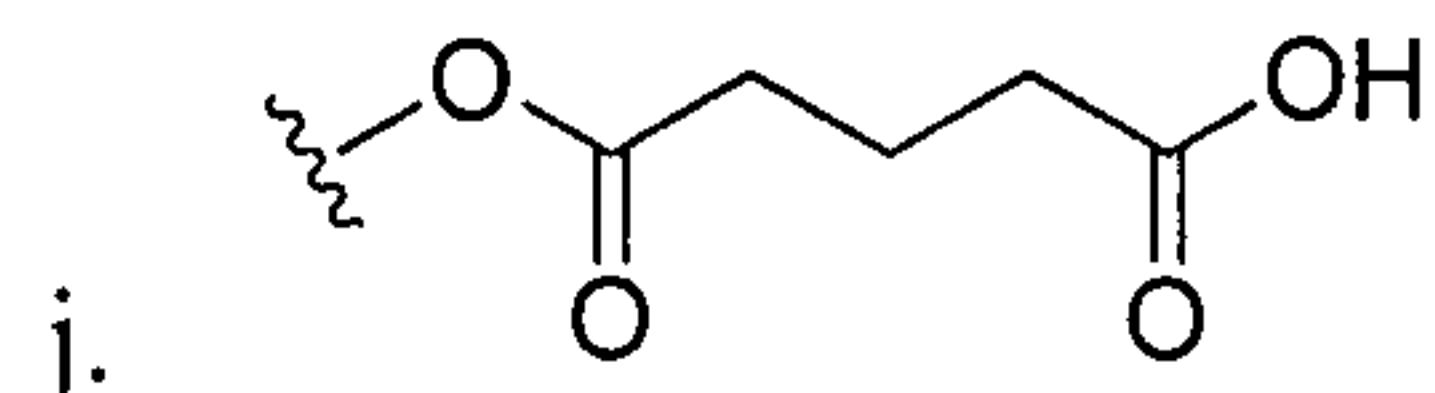
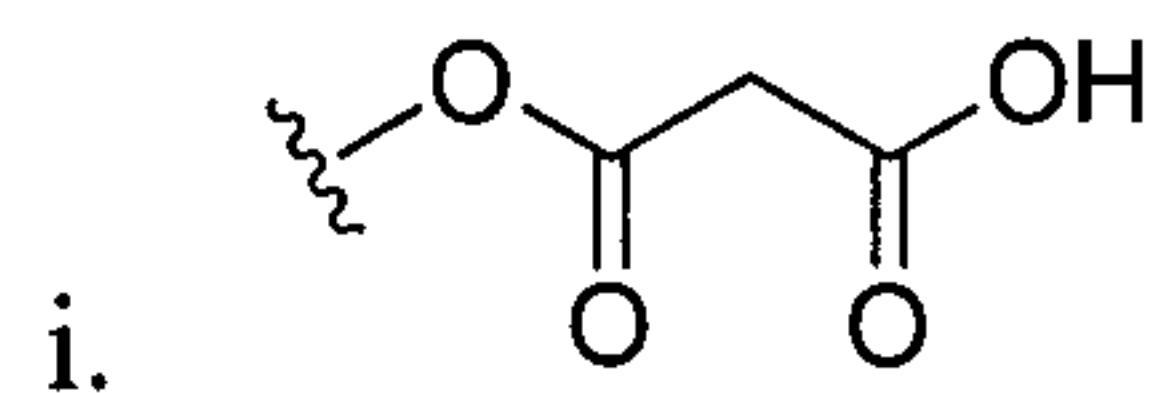
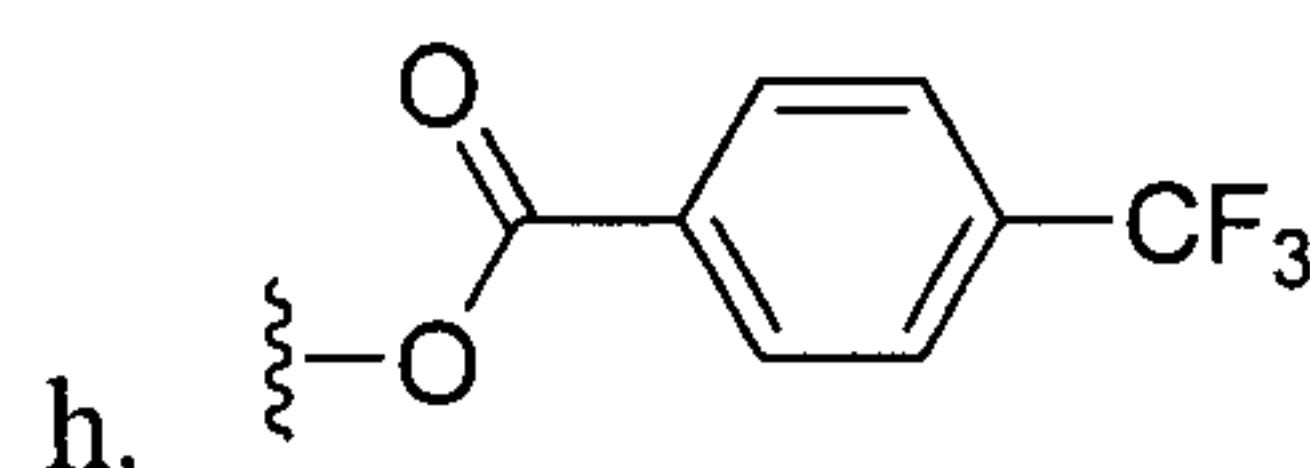
- f. C<sub>1</sub>-C<sub>20</sub> carboxylate;
- g. C<sub>2</sub>-C<sub>20</sub> dicarboxylate;
- h. C<sub>4</sub>-C<sub>20</sub> tricarboxylate;
- i. C<sub>6</sub>-C<sub>20</sub> aryl carboxylate;
- j. C<sub>1</sub>-C<sub>20</sub> alkoxide;
- k. phenoxide; and
- l. a combination of any two or more of (a) through (k); wherein any of the initiating ligands (f)-(h) may optionally be substituted by a hydroxyl group.

16. The method of claim 12, wherein the initiating ligand is selected from the group consisting of:

- a. -Br;
- b. -Cl;
- c. -OH;
- d. -OMe;
- e. -OCOMe;
- f. -OCOBn;

g.



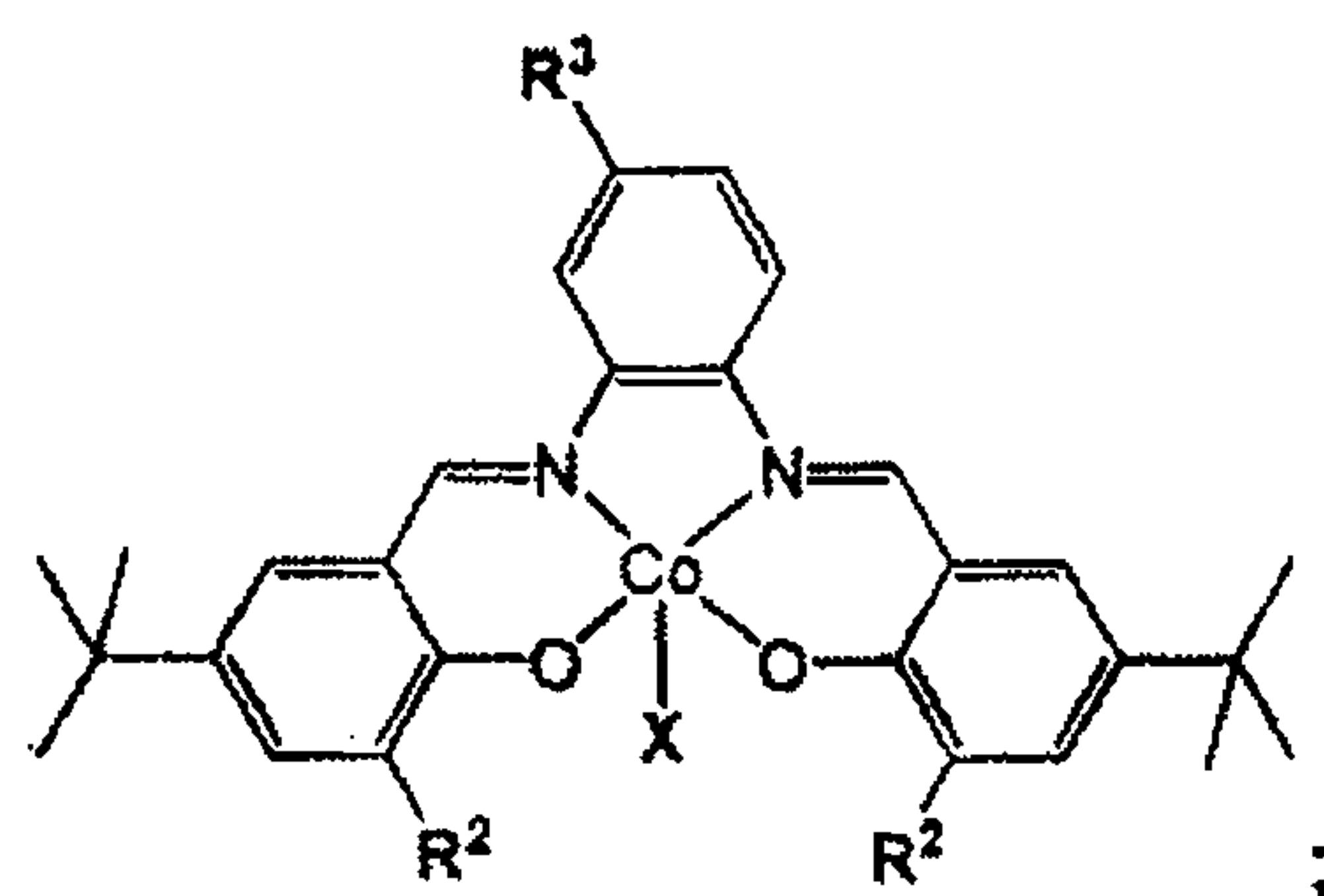


17. The method of claim 10, wherein the C<sub>3</sub>-C<sub>10</sub> alkyl epoxide is propylene oxide.
18. The method of claim 10, wherein the C<sub>3</sub>-C<sub>10</sub> alkyl epoxide is butylene oxide.
19. The method of claim 10, wherein the poly(C<sub>3</sub>-C<sub>10</sub> alkyleneoxide) formed has a number average molecular weight of at least 150,000 g/mol.
20. The method of claim 10, wherein the m-dyad content of the poly(C<sub>3</sub>-C<sub>10</sub> alkyleneoxide) is at least 90%.
21. The method of claim 10, wherein the m-dyad content of the poly(C<sub>3</sub>-C<sub>10</sub> alkyleneoxide) is at least 99%.

22. A method for producing unfractionated isotactic polypropylene oxide having an m-dyad content greater than 81%, comprising the step of homopolymerizing rac-PO in the presence of N,N'-bis(3,5-di-tert-butylsalicylidine)-benzenediamine-Co-initiating ligand.

23. A method of producing unfractionated isotactically-enriched polyalkyleneoxide, comprising the step of:

contacting a monomer comprising C<sub>3</sub>-C<sub>10</sub> alkyl epoxide with a catalyst having the structure:



wherein:

R<sup>2</sup> is selected from the group consisting of:

- a. methyl;
- b. ethyl;
- c. isopropyl; and
- d. tertiary butyl.

R<sup>3</sup> is -H, or -OMe; and

X is selected from the group consisting of:

- a. halide;
- b. cyano;
- c. azide;
- d. hydroxide;
- e. C<sub>1</sub>-C<sub>20</sub> amido;
- f. C<sub>1</sub>-C<sub>20</sub> carboxylate;
- g. C<sub>2</sub>-C<sub>20</sub> dicarboxylate;
- h. C<sub>4</sub>-C<sub>20</sub> tricarboxylate;
- i. C<sub>6</sub>-C<sub>20</sub> aryl carboxylate;
- j. C<sub>1</sub>-C<sub>20</sub> alkoxide;
- k. phenoxide; and
- l. a combination of any two or more of a) through k);

wherein any of the initiating ligands f)-h) may optionally be substituted by a hydroxyl group.

24. Unfractionated isotactic PPO having m-dyad content greater than 90% and M<sub>n</sub> greater than 150,000.
25. The isotactic PPO of claim 24 where the m-dyad content is at least 99%.
26. The isotactic PPO of claim 24 having M<sub>n</sub> greater than 200,000 g/mol.
27. The isotactic PPO of claim 24 having PDI less than 2.0.
28. The isotactic PPO of claim 27 where the PDI is less than 1.75.

29. The isotactic PPO of claim 28 where the PDI is less than 1.50.
30. A method comprising the step of admixing non-isotactic PPO with a PPO of claim 24 or 27.
31. Unfractionated isotactic PPO having m-dyad content greater than 90% and PDI less than 1.50.
32. The isotactic PPO of claim 31 where the m-dyad content is at least 99%.
33. The isotactic PPO of claim 31 having  $M_n$  greater than 200,000 g/mol.
34. A method comprising the step of admixing non-isotactic PPO with a PPO of claim 31.