

ONE-STEP PRODUCTION OF 1,3-PROPANEDIOL FROM
ETHYLENE OXIDE AND SYNGAS WITH A CATALYST
WITH A PHOSPHOLANOALKANE LIGAND

FIELD OF INVENTION

The present invention relates to the synthesis of an aliphatic 1,3-diol, particularly 1,3-propanediol, from ethylene oxide and syngas in one step. More particularly
5 the present invention relates to a catalyst that provides good yields under mild conditions in the one-step synthesis of 1,3-propanediol and demonstrates advantages with respect to cost and performance. The catalyst of the present invention comprises a homogeneous bimetallic
10 cobalt-ruthenium catalyst in combination with a class of bis(phospholano)alkane ligands, solubilized in an ether solvent.

BACKGROUND OF THE INVENTION

Aliphatic 1,3-diols, particularly 1,3-propanediol,
15 have many applications as monomer units for polyester and polyurethane, and as starting materials for the synthesis of cyclic compounds. For example, CORTERRA (trade mark) polymer is a polyester characterized by outstanding properties that is made of 1,3-propanediol (hereafter
20 1,3-PDO) and terephthalic acid. There is much interest in the art in finding new routes for synthesizing 1,3-PDO that are efficient, economical, and demonstrate process advantages.

US-A-3463819 and US-A-3456017 teach the
25 hydroformylation of ethylene oxide to produce 1,3-propanediol and 3-hydroxypropanal (hereafter 3-HPA) using a tertiary phosphine-modified cobalt carbonyl catalyst.

US530491 discloses a method of hydroformylating ethylene oxide to 3-hydroxypropanal and 1,3-propanediol in a single step using an improved catalyst system comprising a cobalt-tertiary phosphine ligand in
5 combination with a ruthenium catalyst. In , 1,3-PDO and 3-HPA are produced by intimately contacting an oxirane, particularly ethylene oxide (hereafter EO), a ditertiary phosphine-modified cobalt carbonyl catalyst, a ruthenium catalyst promoter, and syngas (carbon monoxide and
10 hydrogen) in an inert reaction solvent at hydroformylation reaction conditions. A PDO yield of up to 86-87 mole% is reported, using a catalyst comprising cobalt ligated with 1,2-bis(9-phosphabicyclononyl)ethane as bidentate ligand, and either triruthenium(0)
15 dodecacarbonyl or bis[ruthenium tricarbonyl dichloride] as cocatalyst. Also see US5304686 which discloses the synthesis of 3-hydroxypropanal using a ditertiary phosphine-modified cobalt carbonyl catalyst and a catalyst promoter.

20 The production of 1,3-PDO in one step with minimal impurities and byproducts involves recycle and requires a catalyst system with good stability both during 1,3-PDO synthesis and during product recovery and recycle. It is desirable in the art to identify alternative catalyst
25 systems that demonstrate potential advantages in the one-step production of 1,3-PDO.

WO01/72675 discloses a one step process for preparing a 1,3-diol. Example 5 of WO01/72675 discloses a catalyst composition which comprises dicobalt
30 octacarbonyl, triruthenium dodecacarbonyl and a (R,R)1,2-bis(dimethylphospholano) ethane ligand in a Co:Ru:ligand ratio of 2:1:2 in a methyl-t-butyl ether solvent and a dimethyldodecylamine promoter. Example 5 also discloses a

process for the preparation of propanediol wherein the process comprises contacting at 80°C ethylene oxide with dicobalt octacarbonyl, triruthenium dodecacarbonyl and a (R,R)1,2-bis(dimethylphospholano)ethane ligand in a
5 Co:Ru:ligand ratio of 2:1:2 in a methy-t-butyl ether solvent and a dimethyldodecylamine promoter wherein a 1:1 ratio of carbon monoxide and hydrogen is added to maintain a reaction pressure between 10.4 to 11.1 Mpa.

10 SUMMARY

In accordance with the foregoing, the present invention provides a new class of ligands for use in a hydroformylation/hydrogenation catalyst composition. The ligands of the present invention provide potential
15 advantages with respect to cost and performance. The

present invention provides a catalyst composition comprising:

- a) a cobalt component comprising one or more non-ligated cobalt compounds; and
- 5 b) a ruthenium component comprising in major part a ruthenium carbonyl compound ligated with a phospholanoalkane ligand.

The novel oxirane hydroformylation catalyst of the present invention involves a complex that is postulated to be a cobalt-ruthenium-phospholanoalkane complex. One characterizing feature of the new catalyst is the use of a phospholanoalkane ligand ligated to ruthenium rather than cobalt, as is the case in US-A-5304691. A number of phospholanoalkane ligands are effective, particularly bidentate, bis(phospholano)alkanes.

The invention also provides a one step process for preparing a 1,3-diol, comprising the reaction of an oxirane with syngas at hydroformylation conditions in an inert solvent in the presence of the catalyst composition of the present invention.

In particular, the present invention provides a process for preparing 1,3-propanediol comprising the steps of:

- (a) contacting, in a reaction mixture, ethylene oxide, carbon monoxide, hydrogen, an inert reaction solvent, and a catalyst composition comprising:
 - (i) one or more non-ligated cobalt carbonyl compounds; and
 - 30 (ii) a ruthenium carbonyl compound ligated with a phospholanoalkane moiety; and
- (b) heating said mixture to a temperature within the range from 30 to 150°C and a pressure of at least 100 psi

(690 kPa) for a time effective to produce a two-phase reaction product mixture comprising an upper phase comprising a major portion of the solvent, at least 50 wt% of the catalyst composition, plus unreacted ethylene oxide, and a lower phase, which comprises a major portion of 1,3-propanediol.

BRIEF DESCRIPTION OF THE DRAWINGS

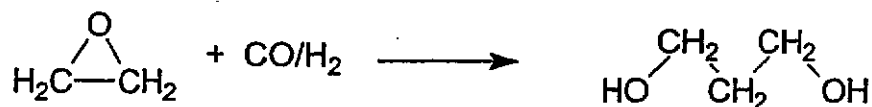
The present invention will now be described by way of example with reference to the accompanying drawings in which:

Figure 1 is a typical IR spectrum of the cobalt-ruthenium-1, 2-bis[(2R, 5R)-2,5-dimethylphospholano]ethane (BDMPE) catalyst during the one-step conversion of EO to 1,3-PDO synthesis, where the initial Co-Ru-BDMPE ratios are 1:0.67:1.2; and

Figure 2 is a cascade plot of the same cobalt-ruthenium-1, 2-bis[(2R, 5R)-2,5-dimethylphospholano]ethane (BDMPE) catalyst during EO to 1,3-PDO synthesis.

DETAILED DESCRIPTION OF THE INVENTION

The selective hydroformylation/hydrogenation of ethylene oxide to 1,3-PDO in one step, represented by:



has been demonstrated using a bimetallic cobalt-ruthenium homogeneous catalyst system in combination with a class of bis(phospholano)alkane ligands, solubilized in an inert reaction solvent. For example, a cobalt-ruthenium-1, 2-bis(2,5-dimethylphospholano)ethane catalyst solubilized in methyl tert-butyl ether (MTBE) can provide up to 70 mole% yield of 1,3-PDO, basis EO charged, during its generation from EO plus syngas.

Generally the one-step process for synthesizing 1,3-PDO comprises intimately contacting ethylene oxide, carbon monoxide and hydrogen (syngas), and a bimetallic catalyst in a liquid-phase solution in an inert reaction solvent at a temperature of from 30 to 150°C, and an elevated pressure, preferably 100 to 4000 psi (690 to 27580 kPa). In this chemistry important factors include efficient PDO recovery from the crude oxonated product solutions, and recycle of the active bimetallic catalyst complex.

In the present invention the 1,3-diols are made by charging an oxirane, Co-Ru-phospholanoalkane complex, reaction solvent, and optional cocatalyst and/or catalyst promoter to a pressure reactor with the introduction of syngas (a mixture of hydrogen and carbon monoxide), suitably in a molar ratio of $H_2:CO$ of 1:1 to 8:1, preferably 2:1 to 6:1, under hydroformylation conditions.

The process of the present invention may be carried out as a batch-type process, continuous process, or a mixture thereof.

In the preferred embodiment of the present invention separate, combined or staged streams of EO, syngas and catalyst are charged to a reaction vessel, which can be a pressure reaction vessel such as a bubble column or a stirred autoclave, operated batch-wise or in a continuous manner.

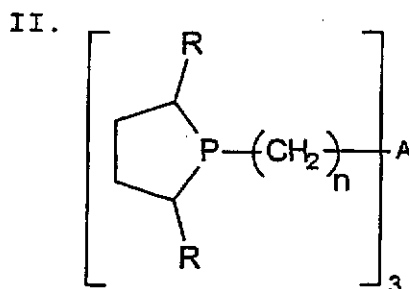
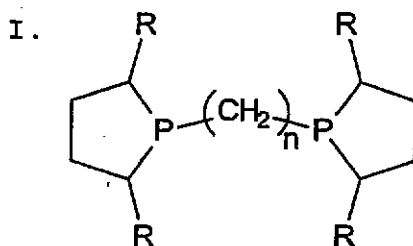
Oxiranes of up to 10 carbon atoms, preferably up to 6 carbon atoms, and ethylene oxide in particular may be converted into their corresponding 1,3-diols by the hydroformylation reaction with syngas in the presence of the catalyst complex of the present invention.

An essential part of the present invention is the use of the Co-Ru-phospholanoalkane complex. The complex

of the present invention is believed to comprise a novel class of ruthenium-modified catalysts. The characterizing feature of this novel class involves an oxidized ruthenium metal that is ligated to a phospholanoalkane ligand, with a cobalt compound as the counter ion.

The oxidation state of the ruthenium atom is not entirely certain (in theory, ruthenium may have a valence of 0 to 8), and may even change during the course of the hydroformylation reaction. Accordingly, the molar ratio of ruthenium to cobalt may vary within relatively broad ranges. Sufficient cobalt(0) should be added to completely oxidize all of the complexed ruthenium employed. An excess of cobalt can be added, but is not of particular value. Suitably, the molar ratio of Ru:Co may vary from 4:1 to 1:4, preferably from 2:1 to 1:4, more preferably from 1:1 to 1:2.

A number of phospholanoalkane ligands have been identified as effective for the one step PDO synthesis using the cobalt-ruthenium catalyst couple. Suitable phospholanoalkanes include phospholane substituted alkane compounds of formula I and II as follows:



where, in both Formula I and II, R is a lower alkyl, trifluoromethyl, phenyl, substituted phenyl, aralkyl, or ring-substituted aralkyl; and n is an integer from 1 to 12; and for formula II, A is CCH₃, CH, N or P. Preferred
5 are compounds of formula I and II wherein R is a lower alkyl of C₁ to C₆ alkyl and n is 1 to 3. Most preferred are those compounds of formula I and II wherein R is methyl and n is 1 to 3.

Examples of such compounds include, but are not
10 limited to, 1,2-bis(phospholano)ethane, 1,2-bis(2,5-dimethylphospholano)ethane, 1,2-bis[(2R, 5R)-2,5-dimethylphospholano]ethane; 1,2-bis[(2S, 5S)-2,5-dimethylphospholano]ethane; 1,3-bis(2,5-dimethylphospholano)propane; tris[(2,5-
15 dimethylphospholano)methyl]methane; tris[(2,5-dimethylphospholano)ethyl]amine; and 1,1,1-tris[(2,5-dimethylphospholano)ethyl]ethane.

Particularly useful, as demonstrated in the examples, in the present invention are bidentate,
20 bis(phospholano)alkanes such as, for example, 1,2-bis[(2R, 5R)-2,5-dimethylphospholano]ethane (BDMPE), 1,2-bis[(2S, 5S)-2,5-dimethylphospholano]ethane, a racemic mixture of the two, plus 1,2 bis(phospholano)ethane.

Suitable cobalt sources include salts that are
25 reduced to the zero valence state by heat-treatment in an atmosphere of hydrogen and carbon monoxide. Examples of such salts comprise, for instance, cobalt carboxylates such as acetates and alkanoates of 6 to 12 carbon atoms such as octanoates, which are preferred, as well as
30 cobalt salts of mineral acids such as chlorides, fluorides, sulphates and sulphonates. Operable also are mixtures of these cobalt salts. It is preferred, however, that when mixtures are used, at least one

component of the mixture be a cobalt alkanoate of 6 to 12 carbon atoms, preferably cobalt octanoate. The reduction may be performed prior to the use of the catalysts, or it may be accomplished simultaneously with the

5 hydroformylation process in the hydroformylation zone.

The counter ion, for best results, is believed to be a cobalt carbonyl, such as the cobalt tetracarbonyl anion, $[\text{Co}(\text{CO})_4]^-$, having a characteristic IR band in the region 1875 to 1900 cm^{-1} , particularly in the region 1888
10 cm^{-1} . However, this ion in the active catalyst can be a modification thereof. Cobalt carbonyls can be generated by reaction of the starting cobalt source such as cobalt octanoate with synthesis gas.

The molar stoichiometry ratio of cobalt:ruthenium:
15 phospholanoalkane ligand is suitably in the range of 0.5 to 4 moles cobalt : 0.25 to 2 moles ruthenium: 0.4 to 3 moles phospholanoalkane ligand. A preferred range would be 1 to 3 moles cobalt: 0.3 to 1.5 moles ruthenium: 0.5 to 2 moles phospholanoalkane ligand, for example
20 1:0.7:1.2. A formulation that worked well, for example, was cobalt: ruthenium:1,2-bis(2,5-dimethylphospholano)ethane in molar stoichiometry of 1:0.67:1.2, respectively. Unligated ruthenium carbonyl is believed to be far less effective, and the catalyst
25 preparation therefore seeks to ligate each ruthenium atom. It is preferred that the molar ratio of ruthenium to cobalt be from 1:4 to 4:1.

In the present invention, the preferred method of preparing the cobalt-ruthenium-phospholanoalkane complex
30 is the self-assembly method, wherein all catalyst components are brought together at the same time. As demonstrated in Example 1, the cobalt-ruthenium-

phospholanoalkane complexes may be generated by self-assembly, in one step, when solubilized in a suitable ether solvent under synthesis gas conditions. The conditions and, in particular, the solvent, are selected
5 such as to favour the formation of a ligated ruthenium species, rather than a ligated cobalt species. The presence of the Ru-ligated species rather than the Co-ligand species may be confirmed by e.g. IR analysis.

Also within the scope of the present invention is
10 the stepwise or sequential design preparation of the catalyst as follows. The first step in the stepwise preparation is synthesis of the Ru-phospholanoalkane complex. This may be done by bringing a suitable ruthenium source, e.g. triruthenium dodecacarbonyl, in
15 contact with the selected ligand. Alternatively, other readily available ruthenium carbonyl derivatives, such as ruthenium dicarbonyl acetate polymer and ruthenium(II) tricarbonyl dichloride, dimer may be employed instead of triruthenium dodecacarbonyl. Further alternatives
20 include the use of less expensive ruthenium sources that, under a syngas atmosphere, will in-situ form ruthenium carbonyl species. These less expensive ruthenium sources may include, for example, ruthenium(IV) oxide, hydrate, ruthenium(III) chloride, and ruthenium-on-carbon.

25 The molar ratio of phospholanoalkane ligand to ruthenium may be 4:1 to 1:2, preferably about 2:1.

The ruthenium-phospholanoalkane complex may, for instance, be made by reacting triruthenium dodecacarbonyl with a stoichiometric amount of a selected ligand in a
30 solvent at a temperature within the range of 25 to 150°C, suitably 100 to 110°C, under a carbon monoxide or synthesis gas atmosphere, for 1 to 24 hours (i.e. until

completion). At this point, optionally, said ruthenium-ligand complex may be isolated as a discrete material.

Next, in the stepwise method, the Ru-ligand complex is brought into contact with a suitable cobalt compound by means of a redox reaction to form the Ru-Co-ligand complex, again at the aforementioned (noncritical) conditions. A suitable cobalt source is cobalt octanoate, but other cobalt complexes and salts may be used as well. For instance, the selected cobalt octanoate, and optional promoters, if any, are added to the solution which is then maintained at the elevated temperature (from 25 to 150°C) for a time of 15 minutes to 24 hours. Again, optionally, the new cobalt-ruthenium-phospholanoalkane complex may be isolated and characterized.

Typically, whether said active Co-Ru-phospholanoalkane complex is generated by self assembly, or step-wise, it exhibits characteristic IR bands, particularly a strong cobalt carbonyl band in the region 1875 to 1900 cm^{-1} due to the $[\text{Co}(\text{CO})_4]^-$ anion, plus a series of three or four ruthenium-carbonyl bands in the 1900 to 2200 cm^{-1} region that are postulated to be due to cationic ruthenium carbonyl species.

The conditions at which these compounds are allowed to form a complex are not critical. Temperature and pressure may vary within the ranges given below with respect to the hydroformylation reaction, for example 25 to 150°C. Syngas may be used as gas cap during the complex formation. It is preferable to use a solvent, preferably the solvent used in the hydroformylation reaction. Obviously, this solvent should be capable of dissolving the active catalyst, without affecting its

properties. Suitable solvents include the ethers described below for use in the hydroformylation process, in particular branched alkyl ethers, such as, for example MTBE.

5 In the one step hydroformylation/hydrogenation using the catalyst composition of the present invention, the optimum ratio of oxirane in the feed to Co-Ru-ligand complex will, in part, depend upon the particular complex employed. However, molar ratios of oxirane to the cobalt
10 within the Co-Ru-ligand complex from 2:1 to 10,000:1 are generally satisfactory, with molar ratios of from 50:1 to 500:1 being preferred.

 Where the oxirane is EO, the EO will preferably be maintained throughout the reaction in a concentration not
15 less than 0.2 % by weight, generally within the range of 0.2 to 20 % by weight, preferably 1 to 10 % by weight, based on the total weight of the reaction mixture.

 The reaction solvent should be inert, meaning that it is not consumed during the course of the reaction.
20 Ideal solvents for the invention process will solubilize the feed and products during the course of the reaction, but allow phase separation at reduced temperatures. Suitable solvents are described in US-A-5304691. Good results may be achieved with alkyl ethers, particularly
25 branched alkyl ethers, and more particularly tertiary carbon atom-containing alkyl ethers. The solvent used to demonstrate the present invention was methyl-tert-butyl ether.

 Promoters may be employed. Suitable promoters are
30 described in US-A-5304691, previously cited. Examples of promoters that work well, are readily available, and have demonstrated the promotion of EO conversion are tertiary amines such as N, N-dimethyldodecylamine and

triethylamine, as well as alkali salts such as sodium acetate.

The components of the feed streams are contacted in a suitable reaction solvent in the presence of the catalyst complex of the present invention. The process of the present invention can be carried out in a continuous mode, while maintaining said EO concentration, by, for instance, staged EO addition.

For best results, the one step hydroformylation/hydrogenation is conducted under conditions of elevated temperature and pressure. Reaction temperatures range from 30 to 150°C, preferably from 50 to 125°C, and most preferably from 60 to 110°C.

The reaction pressure (total pressure, or partial pressure if inert gaseous diluents are used) should be at least 100 psi (690 kPa). A suitable operating pressure is in the range of 100 psi (690 kPa) to 4000 psi (27,580 kPa), preferably from 1000 psi to 2000 psi (6900 to 13,790 kPa), and most preferably about 1500 psi (10,340 kPa) $\pm$ 250 psi (1725 kPa). In a batch process, the reaction will generally be complete within 1 to 5 hours.

At the conclusion of the hydroformylation reaction, the 1,3-PDO is recovered from the product mixture by conventional methods such as selective extraction, fractional distillation, phase separation and selective crystallization. The unreacted starting materials as well as the catalyst and reaction solvent may be, and preferably are, recycled for further use.

Partitioning of the reaction mixture can be promoted by the addition of a phase-split inducing agent. Suitable agents include glycols such as ethylene glycol and linear alkanes such as, for example, dodecane. Such

an agent will be added to the reaction mixture in an amount within the range of 2 to 10% by weight, preferably 4 to 8% by weight, based on the total reaction mixture. Alternative methods include addition of 1,3-propanediol
5 into the reaction mixture to bring product concentration up to the target proportion. Also, miscibilizing alcohols and agents with similar polarity such as ethanol, propanol and isopropanol can be added initially, then removed prior to the subsequent inducement of the
10 phase separation.

Commercial operation will require efficient catalyst recovery with multiple cycles of essentially complete recycle of catalyst to the reaction. The preferred catalyst recovery process involves separation of the two
15 liquid phase mixture noted previously and recycle of the bulk solvent phase to the reactor and return therewith of at least 60 to 90 % by weight of the starting catalyst.

In a preferred manner of running the process, reaction conditions such as oxirane concentration,
20 catalyst concentration, solvent, product concentration and reaction temperature are selected so as to achieve a homogeneous reaction mixture at elevated temperatures and cause a partitioning of the reaction mixture into an upper solvent phase, containing much of the catalyst, and
25 a lower phase containing most of the 1,3-propanediol, upon cooling the mixture. Such a partitioning facilitates isolation and recovery of product, recycle of catalyst, and removal of heavy ends from the solvent system. This process is referred to as a phase
30 separation catalyst recycle/product recovery method.

In this process, the reactor contents are allowed to settle or are transferred to a suitable vessel at pressures ranging from atmospheric to near reaction

pressure where, upon slight or considerable cooling, distinct phases may form that are substantially different, being considerably rich in 1,3-propanediol product, or in catalyst and solvent. The phase rich in cobalt-ruthenium-phospholanoalkane complex and solvent is directly recycled for further reaction with feed materials. Product 1,3-PDO is recovered from the product rich phase by conventional methods.

Formulations containing cobalt octanoate in combination with triruthenium dodecacarbonyl and bis(phospholano)alkane ligands provided one-step synthesis of 1,3-PDO when solubilized in suitable ether solvents. The cobalt octanoate-triruthenium dodecacarbonyl-1, 2-bis(2,5-dimethylphospholano)ethane catalyst precursors, solubilized in MTBE, allowed 1,3-PDO to be generated from EO plus syngas in greater than 70 mole% yields (basis EO charged). Here, hydroformylation is conducted at 90°C and 1500 psi (10,340 kPa), using 4:1 (H₂/CO) gas. Typically, the liquid product comprises two phases, wherein the desired 1,3-PDO is concentrated in the heavier phase (B) (See "Phases" column of Tables). For this heavier phase, in Example 1, the estimated 1,3-PDO/HPA product ratio is ca. 52, the 1,3-PDO/EtOH ratio is 83, and the acetaldehyde content only 0.2%.

Said oxonation-active solutions typically display certain signature infrared bands in the regions: 1850 1900 cm⁻¹, 1900 - 2200 cm⁻¹. These spectra are illustrated in Figures 1 and 2 for the Co-Ru-BDMPE system in MTBE during EO to 1,3-PDO synthesis. The PDO synthesis is illustrated in Example 15.

The addition of excess BDMPE to said Co-Ru catalyst solutions results in no significant 1,3-PDO production

and no signature infrared bands in the 1900-2200 cm^{-1} spectral regions (see Table 3, Example 16).

The following examples will serve to illustrate the present invention disclosed herein. The examples are
5 intended only as a means of illustration and should not be construed as limiting the scope of the present invention in any way. Those skilled in the art will recognize many variations that may be made without departing from the spirit of the disclosed present
10 invention.

Example 1

Preparation of 1,3-PDO

To a 100 ml, stirred, Parr autoclave, equipped with the necessary temperature and pressure controls was
15 charged 228 mg (0.66 mmole) of cobalt octanoate, 207 mg (0.80 mmole) of 1,2-bis[(2R, 5R)-2,5-dimethylphospholano]ethane, 23 ml of dry, nitrogen-flushed methyl tert-butyl ether (MTBE), 93 mg (0.48 mmole Ru) of triruthenium dodecacarbonyl, and 17 mg (0.21
20 mmole) of sodium acetate. The autoclave was sealed and pressurised to 1300 psi (8960 kPa) with 4/1(H_2 :CO) synthesis gas, and heated to 130°C for three hours, with stirring, at 1500 psi (10,340 kPa). At this point, the reactor and contents were cooled to 5°C and the gases
25 vented. Ethylene oxide (3.6 gm, 82 mmole) was added to the reactor system and, after repressurising to 1300 psi (8960 kPa) with 4/1(H_2 :CO) syngas, the reactor was heated to 90°C, for 5-6 hours at 1500 psi (10,340 kPa). Additional synthesis gas was supplied as needed.
30 After cooling to ca. 4°C, and venting, 21.07 gm of a two-phase liquid product was collected comprising 16.00 gm of a MTBE-solvent rich phase and 5.07 gm of a 1,3-

propanediol rich phase. Analyses of these two product liquid phases (T and B), plus a subsequent water-wash (24.1 gm) of the reactor, by gc, showed a 1,3-PDO yield, basis EO charged, of 71 mole%. From further gc analyses
5 of the heavier phase (B) it is concluded that the estimated PDO/HPA product ratio is ca. 52, the PDO/EtOH ratio is 83, and the acetaldehyde content is only 0.2%.

Examples 2-17

Examples 2 to 17 were carried out according to the
10 procedures of Example 1. In these runs the cobalt-ruthenium homogeneous catalysts were used in association with a series of bis(phospholano)alkane ligands. Experimental summary data are provided in accompanying Tables 1- 4, where W/W refers to a post water wash of the
15 Parr reactor, and ND is not detected.

1,3-PDO syntheses have been demonstrated using:

- a) A series of P-ligands, including 1,2-bis([(2R, 5R)-2,5-dimethylphospholano]ethane [BDMPE(R, R)], 1,2-bis([(2S, 5S)-2,5-dimethylphospholano]ethane [BDMPE(S, S)],
20 their racemic mixture, as well as 1,2-bis(phospholano)ethane (BPE).
- b) A range of cobalt:ruthenium:phospholano initial catalyst ratios.
- c) A range of operating temperatures (80-100°C),
25 and pressures (500 to 1500 psi; 3550 to 10,340 kPa).
- d) A range of synthesis gas (H₂/CO) compositions.

Table 1

Ex	Catalyst	Solvent	Temp °C	Time EO Uptake (hrs)	Product Phases wt(g)	Conc. (%) PDO HPA	PDO Production (mmole)	PDO Sel. (%)	PDO Yield (mole%)
2	Co-Ru ₃ (CO) ₁₂ ⁻ BDMPE(R,R) (1:0.44:1)	MTBE	100	4	T 17.2 B 3.7 W/W	2.3 1.7 44.9 16.3 6.3 3.4	7.8 19.4 3.4 30.6	35 61	38
3	Co-Ru ₃ (CO) ₁₂ ⁻ BDMPE(R,R) (1:0.67:1.21)	MTBE	100	4	T 16.8 B 4.7 W/W	2.7 0.9 54.7 7.6 7.9 1.9	8.7 31.7 5.1 45.5	46 78	51
4	Co-Ru ₃ (CO) ₁₂ ⁻ BDMPE(R,R) (1:0.88:1.47)	MTBE	100	4.25	T 17.1 B 4.2 W/W	2.7 0.4 58.1 5.3 6.6 N.D.	8.7 28.8 4.1 41.6	53 81	48
5	Co-Ru ₃ (CO) ₁₂ ⁻ BDMPE(R,R) (1:0.67:1.21)	MTBE	100	3.75 ^a	T 16.9 B 3.6 W/W	2.4 1.1 55.0 9.5 9.4 3.0	6.1 20.5 7.2 33.8	42 75	40
6	Co-Ru ₃ (CO) ₁₂ ⁻ BDMPE(R,R) (1:0.67:1.21)	MTBE	80	5 ^a	T 12.9 ^b B 4.9 W/W	3.0 0.5 61.8 67.0 5.7 N.D.	6.1 ^b 37.3 3.4 46.8	63 84	56
7	Co-Ru ₃ (CO) ₁₂ ⁻ BDMPE(R,R) ^b	MTBE	80	6 ^a	T 16.3 B 4.7 W/W	2.2 0.4 62.4 6.8 6.0 1.1	8.5 33.7 4.1 46.3	62 85	56

^a Use 2:1 H₂/CO Gas^b Repeat of Example 6

Table 2

Ex	Catalyst	Solvent	Temp °C	Time EO Uptake (hrs)	Product Phases wt (g)	Conc. (%)	PDO	HPA	PDO Pro- duction (mmole)	PDO Sel. (%)	PDO Yield (mole%)
8	Co-Ru ₃ (CO) 12 ⁻ BDMPE (S,S) (1:0.67:1.21)	MTBE	80	6 ^a	T 17.3 B 4.0 W/W	2.1 61.7 3.9	0.5 7.6 1.1		7.5 29.1 2.5 39.1	65 83	45
9	Co-Ru ₃ (CO) 12 ⁻ BDMPE (R,R) (1:0.44:0.2)	MTBE	100	1.25 ^a	P 20.5 W/W	N.D. N.D.	1.4 N.D.		N.D. N.D. <0.1		<0.1 <0.1
10	Co-Ru ₃ (CO) 12 ⁻ BDMPE (R,R) (1:0.67:1.21)	MTBE	80	6 ^b	T 16.0 B 5.6 W/W	2.2 72.6 4.5	N.D. 1.4 N.D.		7.3 48.2 2.9 58.4	75 95	71
11	Co-Ru ₃ (CO) 12 ⁻ BDMPE (R,R) ^c (1:0.67:1.21)	MTBE	80	5 ^b	T 16.3 B 4.7 W/W	1.9 65.2 9.7	0.2 5.4 N.D.		71.0 37.1 6.4 50.6	63 89	60
12	Co-Ru ₃ (CO) 12 ⁻ BDMPE (R,R) (1:0.67:1.21)	MTBE	80	4.25 ^d	T 16.4 B 4.8 W/W	1.3 58.8 8.3	0.4 6.6 1.6		3.7 30.9 5.6 40.2	46 78	47
13	Co-Ru ₃ (CO) 12 ⁻ BDMPE (R,R) (1:0.67:1.21)	MTBE	80	0.75 ^e	T 19.7 B 0.4 W/W	3.9 61.8 3.7	0.3 2.6 N.D.		8.1 2.2 2.4 12.7	69 80	15

^a Use 2:1 H₂/CO Gas^b Use 4:1 H₂/CO Gas^c Repeat of Example 10^d Use 4/1 H₂/CO at 1000 psi (6900 kPa)^e Use 4/1 H₂/CO at 500 psi (3550 kPa)

Table 3

Ex	Catalyst	Solvent	Temp °C	Time EO Uptake (hrs)	Product Phases wt (g)	PDO Conc. (%)	PDO Pro- duction (mmole)	PDO Sel. (%)	PDO Yield (mole%)
14	Co-Ru ₃ (CO) 12 ⁻ 1,2 BDMPE (RACEMIC) (1:0.67:1.21)	MTBE	80	6 ^a	T 16.6 B 3.6 W/W	PDO 1.3 HPA 63.8 8.1	5.8 26.0 5.2 37.0	54 83	48
15	Co-Ru ₃ (CO) 12 ⁻ BDMPE (R,R) (1:0.67:1.21)	MTBE	80	^b	T 17.0 B 2.0	PDO 1.7 HPA 60.3	8.1 11.9 19.2 27.3	59 78	70
16	Co-Ru ₃ (CO) 12 ⁻ BDMPE (R,R) (1:0.67:3.64)	MTBE	80	^b	P 17.4	PDO <0.1 HPA N.D.	<1	<1	<0.1

^a Use 4:1 H₂/CO Gas^b Run in IR cell

Table 4

Ex	Catalyst	Solvent	Temp °C	Time EO Uptake (hrs)	Product Phases wt (g)	Conc. (%) PDO HPA	PDO Pro- duction (mmole)	PDO Sel. (%)	PDO Yield (mole%)
17	Co-Ru ₃ (CO) ₁₂ ⁻ 1,2 BPE (1:0.67:1.21)	MTBE	80	4 ^a	T 16.7 B 3.7 W/W	4.3 61.9 6.2	14.6 27.1 4.3 46.0	64 90	58

^a Use 4:1 H₂/CO Gas

WE CLAIM:

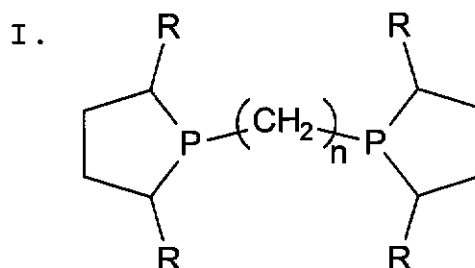
1. A catalyst composition comprising:

(a) cobalt component comprising one or more non-ligated cobalt compounds; and

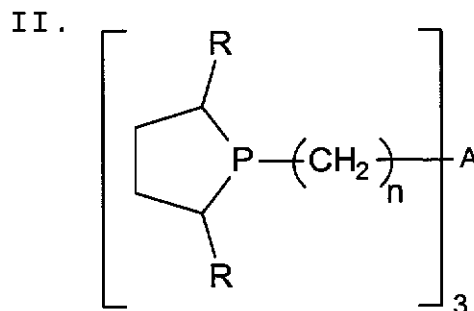
(b) ruthenium component comprising in major part a
 5 ruthenium carbonyl compound ligated with a
 phospholanoalkane ligand, wherein the catalyst
 composition does not comprise dicobalt octacarbonyl,
 triruthenium dodecacarbonyl and a (R,R)1,2-
 bis(dimethylphospholano)ethane ligand in a Co:Ru:ligand
 10 ratio of 2:1:2 in a methyl-t-butyl ether solvent and a
 dimethyldodecylamine promoter.

2. The catalyst composition of Claim 1 solubilized in an ether solvent.

3. The composition of Claim 2 wherein the
 15 phospholanoalkane is represented by:



or



wherein, in both I and II, R is a lower alkyl,
 20 trifluoromethyl, phenyl, substituted phenyl, aralkyl, or

ring-substituted aralkyl; and n is an integer from 1 to 12; and for formula II, A is CCH_3 , CH, N or P.

4. The composition of Claim 3 where, in both I and II, R is a lower alkyl of C_1 to C_6 alkyl and n is 1 to 3.

5. The composition of Claim 4 where, in formula I and II, R is methyl.

6. The composition of Claim 1 where the phospholanoalkane is selected from the group consisting of 1,2-bis(phospholano)ethane, 1,2-bis(2,5-dimethylphospholano)ethane, 1,2-bis[(2R,5R)-2,5-dimethylphospholano]ethane; 1,2-bis[(2S, 5S)-2,5-dimethylphospholano]ethane; 1,3-bis(2,5-dimethylphospholano)propane; tris[(2,5-dimethylphospholano)methyl]methane; tris[(2,5-dimethylphospholano)ethyl]amine; and 1,1,1-tris[(2,5-dimethylphospholano)ethyl]ethane.

7. The composition of Claim 1 wherein the ruthenium compound is selected from the group consisting of ruthenium (II) tricarbonyl chloride, triruthenium dodecacarbonyl, ruthenium dicarbonyl acetate polymer, ruthenium(III) chloride, ruthenium (IV) oxide or its hydrate, and ruthenium-on-carbon.

8. A process for preparing 1,3-propanediol comprising the steps of:

(a) contacting, in a reaction mixture, ethylene oxide, carbon monoxide, hydrogen, an inert reaction solvent, and a catalyst composition comprising:

(i) one or more non-ligated cobalt carbonyl compounds; and

(iii) a ruthenium carbonyl compound ligated with a phospholanoalkane moiety; and

- (b) heating said mixture to a temperature within the range from 30 to 150°C and a pressure of at least 100 psi (690 kPa) for a time effective to produce a two-phase reaction product mixture comprising an upper phase comprising a major portion of the solvent, at least 50 wt% of the catalyst composition, plus unreacted ethylene oxide, and a lower phase, which comprises a major portion of 1,3-propanediol, wherein the process does not comprise contacting at 80°C ethylene oxide with dicobalt octacarbonyl, triruthenium dodecacarbonyl and a (R,R)1,2-bis(dimethylphospholano)ethane ligand in a Co:Ru:ligand ratio of 2:1:2 in a methyl-t-butyl ether solvent and a dimethyldodecylamine promoter wherein a 1:1 ratio of carbon monoxide and hydrogen is added to maintain a reaction pressure between 10.4 to 11.1 Mpa.
9. The process of Claim 8 wherein the catalyst composition is made by a self-assembly method wherein all the components are brought together at the same time under synthesis gas conditions.
10. The process of Claim 8 wherein the catalyst composition is made stepwise wherein the ruthenium compound is reacted with a phospholanoalkane in the presence of syngas at a temperature in the range of 25 to 150°C and subsequently caused to undergo a redox reaction with the cobalt compound at a temperature in the range of 25 to 150°C.