

Process of Manufacturing Polyols

Field

[0001] Embodiments relate to methods of manufacturing polyols using at least a Lewis acid catalyst, polyols prepared using at least the Lewis acid catalyst, and/or polyurethane products prepared using the polyols prepared using at least the Lewis acid catalyst.

Introduction

[0002] Polyether polyols are produced by polymerizing an alkylene oxide in the presence of a starter compound and a catalyst. The starter compound has one or more functional groups the alkylene oxide can react with to begin forming polymer chains. The starter compound may influence the molecular weight and establish the number of hydroxyl groups that the resultant polyether polyol will have.

[0003] With respect to the catalyst for forming polyether polyols, manufacturing is moving toward the use of a double-metal cyanide (DMC) catalyst in place of an alkali metal catalyst (such as a KOH based catalyst). A disadvantage of DMC catalysts is that they may activate slowly, as is taught in U.S. Patent No. 9,040,657. In particular, preparation of polyether polyols using the DMC catalyst may begin with a stage of the reaction known as the catalyst induction period. During this stage of the reaction, the DMC catalyst is believed to become converted in situ from an inactive form into a highly active form that rapidly polymerizes the alkylene oxide as long as the catalyst remains active. This catalyst induction period is typically an indeterminate period of time following the first introduction of alkylene oxide to the reactor. It is common to introduce a small amount of alkylene oxide at the start of the polymerization process and then wait until the catalyst has become activated (as indicated, e.g., by a drop in reactor pressure due to the consumption of the initial alkylene oxide that had been charged into the reactor) before continuing with the alkylene oxide feed. Very little or no polymerization occurs until the catalyst has become activated, such that long activation times have a direct negative impact on the productivity of the process. It is sometimes the case that the catalyst does not become activated at all. Such a failure of the catalyst to activate may result in the abandonment of the attempt, and the process is started over again from the beginning. As such, the activation process results in some loss of productivity under the best circumstances, and under the worst circumstances can cause a loss of the entire batch of starting mixture. Thus, the reduction or elimination of the induction period at the start of the alkoxylation reaction is seen to be highly desirable.

[0004] The disadvantages of the use of conventional Lewis acids such as boron trifluoride to polymerize epoxides is well-known, e.g., as taught in U.S. Patent No. 6,624,321. For example, use of such conventional Lewis acids as catalysts may lead to the formation of volatile low molecular weight cyclic ethers, may require high levels of catalyst loading (which ultimately require the need for a later process stage to remove catalyst from the resultant product), and may lead to catalyst decomposition during which release of a highly corrosive HF side-product and incorporation of fluorine atoms in the backbone of the polymerization product may occur. Further, boron trifluoride is regarded as hazardous material that is also moisture sensitive and difficult to handle.

[0005] The use of tris(pentafluorophenyl)borane catalyst during ring-opening polymerization of an alkylene oxide is taught, e.g., in U.S. Patent No. 6,531,566. The tris(pentafluorophenyl)borane catalyst provides several advantages over conventional Lewis acids such as boron trifluoride. For example, the tris(pentafluorophenyl)borane catalyst is not corrosive, easy to handle, and appreciably more active. However, tris(pentafluorophenyl)borane catalyst produces an undesirable side-reaction leading to formation of aldehydes and acetal linkages in the polyol backbone.

[0006] The use of a dual catalyst package for producing a polyol having a high primary hydroxyl group content, which includes a DMC catalyst and a Lewis acid catalyst such as tris(pentafluorophenyl)borane is disclosed, e.g., in International Publication No. WO 2016/064698. The DMC catalyst enables the production of high molecular weight segments efficiently and the Lewis acid catalyst enables the formation of primary hydroxyl end groups. This method may minimize the residence time of the Lewis acid step and therefore the amount of side-product.

[0007] A method of using a combination of DMC and KOH catalysts to produce EO-capped polyether polyols is taught, e.g., in U.S. Patent Publication No. 2011/0230581. In this process, the DMC catalyst is utilized to polymerize propylene oxide (PO) and KOH catalyst is utilized to promote ethylene oxide (EO) capping. This technology suffers from all the drawbacks of conventional KOH technology, such as slow kinetics and need for catalyst removal or finishing steps in the resultant polyether polyols.

[0008] A method of using a combination of tris(pentafluorophenyl)borane (Lewis acid) and KOH catalysts to product EO-capped polyether polyols is taught in, e.g., U.S. Patent No. 9,388,271. In this process, the tris(pentafluorophenyl)borane catalyst is utilized to polymerize PO in a first step. During the first step, the vapor phase in the autoclave is

circulated through a reaction column and distillation column and back to the autoclave reactor in order to minimize side-product formation. In a second step, the KOH catalyst is utilized to polymerize EO onto the PO chain ends. This process is complicated and may require finishing step(s) to remove KOH catalyst residues.

[0009] Therefore, improvements are sought with respect to producing EO based polyols (such as EO-capped polyols) efficiently in such a way so as to not require a catalyst removal step and/or to changing the selectivity of the Lewis acid catalyst itself, e.g., to improve yield of the desired ethylene oxide-based polyether polyol product (such as the EO capped polyether polyol having a number molecular weight of at least 224 g/mol and EO capping of at least 1 wt% based on a total weight of the resultant polyether polyol). Accordingly, improvements are sought with respect to improving yield of desired products and/or producing non-finishing polyols (i.e., polyols that do not require further finishing).

Summary

[0010] Examples may be realized by providing a method of producing a polyether polyol that includes reacting a low molecular weight initiator with ethylene oxide in the presence of a polymerization catalyst, the low molecular weight initiator having a nominal hydroxyl functionality at least 2, and the polymerization catalyst being a Lewis acid catalyst having the general formula $M(R^1)_1(R^2)_1(R^3)_1(R^4)_{0 \text{ or } 1}$. Whereas, M is boron, aluminum, indium, bismuth or erbium, R^1 , R^2 , and R^3 each includes a same fluoroalkyl-substituted phenyl group, and optional R^4 includes a functional group or functional polymer group. The method further includes forming a polyether polyol having a number average molecular weight of greater than the number average molecular weight of the low molecular weight initiator in the presence of the Lewis acid catalyst.

[0010a] In one aspect, the present disclosure refers to a method of producing a polyether polyol, comprising: reacting a low molecular weight initiator with ethylene oxide in the presence of a polymerization catalyst, the low molecular weight initiator having a nominal hydroxyl functionality of at least 2, and the polymerization catalyst being a Lewis acid catalyst having the general formula $M(R^1)_1(R^2)_1(R^3)_1(R^4)_{0 \text{ or } 1}$, whereas M is boron, R^1 , R^2 and R^3 each is a fluoro/chloro-fluoroalkyl-substituted phenyl group, difluoro/chloro-fluoroalkyl-substituted phenyl group, trifluoro/chloro-fluoroalkyl-substituted phenyl group, or tetrafluoro/chloro-fluoroalkyl-substituted phenyl group, and optional R^4 includes a functional group or functional polymer group, said functional group or functional group polymer being a molecule that contains at least one of the following: water, an

alcohol, an alkoxy, a ketone, an ester, an organosiloxane, an amine, a phosphine, an oxime, and substituted analogs thereof; and forming a polyether polyol having a number average molecular weight of greater than the number average molecular weight of the low molecular weight initiator in the presence of the Lewis acid catalyst.

[0010b] In another aspect, the present disclosure refers to a method of producing a polyether polyol, comprising: reacting a low molecular weight initiator with ethylene oxide in the presence of a polymerization catalyst, the low molecular weight initiator having a nominal hydroxyl functionality of at least 2, and the polymerization catalyst being a Lewis acid catalyst having the general formula $M(R^1)_1(R^2)_1(R^3)_1(R^4)_1$, whereas M is boron, aluminum, indium, bismuth or erbium, R^1 , R^2 and R^3 each includes a same fluoroalkyl-substituted phenyl group, and R^4 includes a functional group or functional polymer group, said functional group or functional group polymer being a molecule that contains at least one of the following: water, an alcohol, an alkoxy, a ketone, an ester, an organosiloxane, an amine, a phosphine, an oxime, and substituted analogs thereof; and forming a polyether polyol having a number average molecular weight of greater than the number average molecular weight of the low molecular weight initiator in the presence of the Lewis acid catalyst.

Detailed Description

[0011] Ethylene oxide (EO) is an important and widely used monomer in the production of polyether polyols. EO polymerization offers the opportunity to significantly increase the reactivity of polyol with polyisocyanates relative to PO polyols by virtue of the resulting primary hydroxyl end groups. Homopolymers of EO such as certain polyethylene glycols, may find limited use in polyurethanes as they may crystallize readily and/or have a high affinity to water. The high affinity of polyethylene glycols to water may be detrimental to the properties of resultant polyurethanes products, e.g., as the products may be sensitive to the humidity in the environment. The use of block structures formed by the addition of short EO segments (referred to as EO capping) to PO and/or BO polyols has been proposed as a compromise between increasing reactivity with isocyanates and minimizing difficulties associated with processability and water affinity. Another approach is to copolymerize EO and PO and/or BO (e.g., mixed feed polyols) to form polyols that are composed of statistical mixtures of EO and PO and/or BO. From a reactivity point of view, the highest primary hydroxyl content and therefore reactivity may be achieved using the capping approach.

[0012] Currently, EO-capped polyols on an industrial scale are typically produced utilizing KOH-catalyzed polymerization technology. Also, many have found that DMC catalysts are typically unable to efficiently polymerize EO at a commercial scale. The use of conventional Lewis acids to polymerize EO is not preferred due to side-reactions. For example, these side-reaction may result in volatile side-products such as small cyclic ethers and acetaldehyde. As a result, the yield of the reaction may be greatly diminished. In addition, extra purification steps may be needed to obtain a product of sufficiently high quality. By yield it is meant herein percent yield, which is well-known as determined according to the following equation:

$$\% \text{ yield} = (\text{actual yield})/(\text{theoretical yield}) \times 100$$

As is well-known, the actual yield and theoretical yield may be based on weight percent or mole percent. The actual % yield is a dimensionless number.

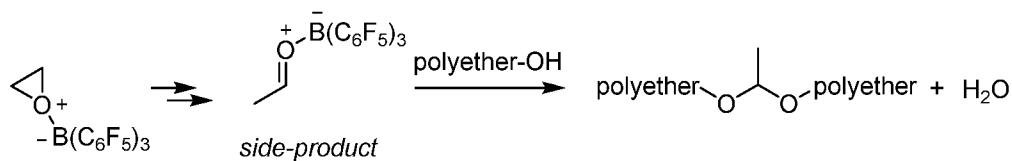
[0013] As discussed in International Publication No. WO 2012/091968, certain Lewis acids that may essentially require no activation time have been evaluated as polymerization catalysts. However, some Lewis acids may become deactivated rapidly and may not be capable of producing high molecular weight polymers or of obtaining high conversions of alkylene oxides to polymer. Further, high amounts of alkaline catalysts, such as sodium hydroxide may require treatment such as filtration and/or acid finishing/neutralization (e.g.,

as discussed in U.S. Patent No. 5,468,839) to reduce the base content of the resultant product. The use of a sufficiently low amount of Lewis acid catalysts and optionally a DMC catalyst may eliminate the need for such treatment, while also providing for control and/or selectivity. However, certain Lewis acids may promote undesirable side reactions. The presence of certain side products in a polyol product may necessitate performing an additional finishing step on the resultant product.

[0014] Embodiments relate to certain Lewis acid catalysts, and processes using such Lewis acid catalysts, that may provide advantages with respect to minimizing side reactions such as those that produce undesired side-products and increasing yield of the desired products, while still allowing for precise control of the polymerization reaction. By Lewis acid it is meant a substance that can accept a pair of electrons. In other words, a Lewis acid is an electron-pair acceptor.

[0015] Embodiments may relate to providing polyol polymers having a desirable high yield, e.g., of EO capped polyether polyols and/or polyols prepared using a mixed feed of EO and another alkylene oxide. By EO capped polyols it is meant polyether polyols chains that have the addition of ethylene oxide (e.g., ethylene oxide only and essentially excluding intended addition of any other alkylene oxides such as propylene oxide and butylene oxide) on at least one end of such chain. EO capping may be performed on a polyether polyol (e.g., derived from propylene oxide, ethylene oxide, and/or butylene oxide). EO capping may result in a polyol having a high primary hydroxyl content (e.g., at least 30%, at least 40%, at least 50%, at least 60%, at least 70%, at least 80%, etc.) For a mixed feed process, copolymerization of EO and another alkylene oxide such as propylene oxide and/or butylene oxide may be performed on a starter compound and may result in a polyol having a higher primary hydroxyl content than that prepared with a feed of propylene oxide or butylene oxide alone.

[0016] During the polymerization process to form a polyether polyol, some Lewis acid catalysts such as the tris(pentafluorophenyl)borane catalyst, may have a disadvantage in that certain side reactions may occur at undesirable levels (depending on the outcome desired). An example of such side reactions is the tris(pentafluorophenyl)borane catalyst-assisted formation of acetaldehyde as shown below in Schematic 1, which may occur in the presence of alcohols and may lead to the lack of desired chemoselectivity for the resultant polyether polyol. Further, high amount of formation of acetaldehyde or other volatile side-products may result in poor yield.

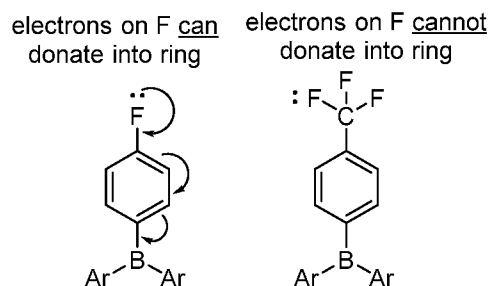


Schematic 1

[0017] Further, a subsequent acetaldehyde-alcohol coupling reaction to form an acetal linkage, may result in higher molecular weight species as compared to when the coupling is not present and/or may make molecular weight control challenging especially at a commercial scale. Also, the water by-product that results from the coupling reaction could potentially consume monomer and result in the formation of diols and/or alter the catalytic activity of the tris(pentafluorophenyl)borane catalyst. Further, when the resultant product is used to form a polyurethane polymer, acetal linkages may be found at undesirable levels, which could potentially degrade over the life of the polyurethane polymer based product depending on the application.

[0018] Accordingly, in exemplary embodiments, a reaction system for forming a polyether polyol (such as an ethylene oxide based polyol) uses a Lewis acid catalyst (e.g., in a low amount such that filtration and acid finishing/neutralization are not required for the resultant polyether polyol) that minimizes side reactions and optionally may be combined with a DMC catalyst. For example, it is proposed to use triarylborane catalysts that have fluoroalkyl-substituted phenyl groups, which may allow for improvements with respect to selectively minimizing side reactions so as to improve yield of desired EO based products and/or for precise control of the polymerization reaction (such as an EO-capping reaction).

[0019] In particular, it has been found that triarylborane catalysts containing fluoroalkyl substituents may significantly decrease the side-reactions leading to lower acetal linkages in the backbone. It is believed that the fluoroalkyl groups may impart unique properties to the metal (such as boron) active center. For example, the Hammett constant (σ) for a fluorine group in the para position $\sigma_p = 0.06$ whereas that for a CF_3 group in the para position is 0.54. As such, a CF_3 group may act as a unique electron withdrawing group, which is in part related to the inability of F atoms to donate into the ring.



[0020] Embodiments, relate to forming a polyether polyol (e.g., an ethylene oxide based polyol) with a high yield. The polyether polyol may have a relatively high number average molecular weight (i.e., greater than 500 g/mol, greater than 1000 g/mol, greater than 2,500 g/mol such as from 2,600 g/mol to 12,000 g/mol, 3,000 g/mol to 6,000 g/mol, etc.) The polyether polyol may have a specified primary hydroxyl group content (e.g., from 30 % to 95 %, based on a total number of hydroxyl groups). For example, the Lewis acid catalyst may be used to enable a desired amount of ethylene oxide capping for the resultant polyether polyol as a means toward achieving a desired primary hydroxyl group content. Certain primary hydroxyl content values may be sought after for specific end use applications of polyurethanes, based on a desired reactivity speed. For example, some end use applications may seek a rapid reactivity speed, for which a relatively higher primary hydroxyl group content may be sought. Other end use applications may seek a relatively slow reactivity speed, for which a lower primary hydroxyl group content may be sought.

[0021] According to exemplary embodiments, a catalyst component for forming the polyether polyol may utilize the Lewis acid catalyst and optionally the DMC catalyst. For example, the Lewis acid catalyst may be used without the DMC catalyst, or the DMC catalyst and the Lewis acid catalyst may be used simultaneously or sequentially added. For example, in a DMC-Lewis acid dual catalyst system, a polymerization method may include initially adding a DMC catalyst and later adding the Lewis acid catalyst that is separately provided and allowed to react at a lower temperature than the temperature at which the DMC catalyst was added. The Lewis acid catalyst may be active at a lower temperature range (e.g., from 60°C to 115°C) than a temperature range at which the DMC catalyst may be active (e.g., from 125°C to 160°C).

[0022] Polyether polyols include polyols that have multiple ether bonds. Exemplary polyether polyols include polyether hybrid polyols (such as polyether carbonate polyols and polyether ester polyols). The polyether polyols are produced by polymerizing an alkylene oxide component that includes at least one alkylene oxide and an initiator component that includes at least one initiator compound. The initiator compound has one or more

functional groups at which the alkylene oxide can react to begin forming the polymer chains. The main functions of the initiator compound are to provide molecular weight control and to establish the number of hydroxyl groups that the monol or polyol product will have. The polyether carbonate may be produced by polymerizing carbon dioxide, at least one alkylene oxide, and an initiator compound. The polyether ester may be produced by polymerizing at least one alkylene oxide with a carboxylic acid initiator.

Lewis Acid Catalyst

[0023] According to exemplary embodiments, the Lewis acid catalyst has the general formula $M(R^1)_1(R^2)_1(R^3)_1(R^4)_{0 \text{ or } 1}$, whereas M is boron, aluminum, indium, bismuth or erbium, R^1 , R^2 , and R^3 are each a fluoroalkyl-substituted phenyl group, and optional R^4 is a functional group or functional polymer group. The M in the general formula may exist as a metal salt ion or as an integrally bonded part of the formula. R^1 , R^2 , and R^3 are each a fluoroalkyl-substituted phenyl group. R^1 , R^2 , and R^3 are each the same fluoroalkyl-substituted phenyl group.

[0024] R^1 , R^2 , and R^3 may include the fluoroalkyl-substituted phenyl group or may consist essentially of the fluoroalkyl-substituted phenyl group. Similarly, R^4 may include the functional group or functional polymer group, or consist essentially of the R^4 is the functional group or functional polymer group.

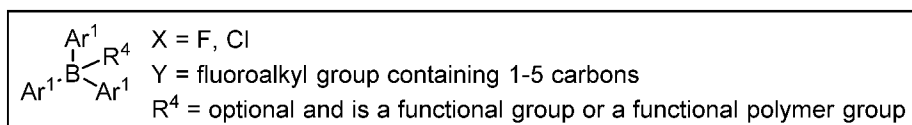
[0025] With respect to R^1 , R^2 , and R^3 , by fluoroalkyl-substituted phenyl group it is meant a phenyl group that includes at least one hydrogen atom replaced with a fluoroalkyl group, which is an alkyl group with at least one hydrogen atom replaced with a fluorine atom. For example, the fluoroalkyl group may have the structure $C_nH_mF_{2n+1-m}$, whereas n is greater than or equal to 1 and less than or equal to 5. Also, m is a number that reflects a balance of the electrical charges to provide an overall electrostatically neutral compound, e.g., can be zero, one or greater than one. The phenyl group of the fluoroalkyl-substituted phenyl may be substituted to include other groups in addition to the at least one fluoroalkyl group, e.g., a fluorine atom and/or chlorine atom that replaces at least one hydrogen of the phenyl group. For example, R^1 , R^2 , and R^3 may be a fluoro/chloro-fluoroalkyl-substituted phenyl group (meaning one fluoro or chloro group and at least one fluoroalkyl group are substituted on the phenyl group), difluoro/chloro-fluoroalkyl-substituted phenyl group (meaning two fluoro, two chloro, or a fluoro and chloro group and at least one fluoroalkyl group are substituted on the phenyl group), trifluoro/chloro-fluoroalkyl-substituted phenyl group (meaning three fluoro, three chloro, or a combination of fluoro and chloro groups

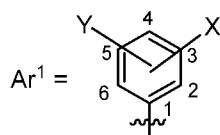
totaling three and at least one fluoroalkyl group are substituted on the phenyl group), or tetrafluoro/chloro-fluoroalkyl-substituted phenyl group (meaning four fluoro, four chloro, or a combination of fluoro and chloro groups totaling four and one fluoroalkyl group are substituted on the phenyl group).

[0026] With respect to optional R^4 , the functional group or functional polymer group may be a Lewis base that forms a complex with the Lewis acid catalyst (e.g., a boron based Lewis acid catalyst) and/or a molecule or moiety that contains at least one electron pair that is available to form a dative bond with a Lewis acid. The Lewis base may be a polymeric Lewis base. By functional group or functional polymer group it is meant a molecule that contains at least one of the following: water, an alcohol, an alkoxy (examples include a linear or branched ether and a cyclic ether), a ketone, an ester, an organosiloxane, an amine, a phosphine, an oxime, and substituted analogs thereof. Each of the alcohol, linear or branched ether, cyclic ether, ketone, ester, alkoxy, organosiloxane, and oxime may include from 2-20 carbon atoms, from 2-12 carbon atoms, from 2-8 carbon atoms, and/or from 3-6 carbon atoms.

[0027] For example, the functional group or functional polymer group may have the formula $(OYH)_n$, whereas O is O oxygen, H is hydrogen, Y is H or an alkyl group, and n is an integer (e.g., an integer from 1 to 100). However, other known functional polymer groups combinable with a Lewis acid catalyst such as a boron based Lewis acid catalyst may be used. Exemplary cyclic ethers include tetrahydrofuran and tetrahydropyran. Polymeric Lewis bases are moieties containing two or more Lewis base functional groups such as polyols and polyethers based on polymers of ethylene oxide, propylene oxide, and butylene oxide. Exemplary polymeric Lewis bases include ethylene glycol, ethylene glycol methyl ether, ethylene glycol dimethyl ether, diethylene glycol, diethylene glycol dimethyl ether, triethylene glycol, triethylene glycol dimethyl ether, polyethylene glycol, polypropylene glycol, and polybutylene glycol.

[0028] Exemplary Lewis acid catalysts have the following structure in which each of Ar^1 includes at least one fluoroalkyl (Y) group substituted on a phenyl group and optionally at least one fluoro or chloro (X) substituted on the phenyl group:

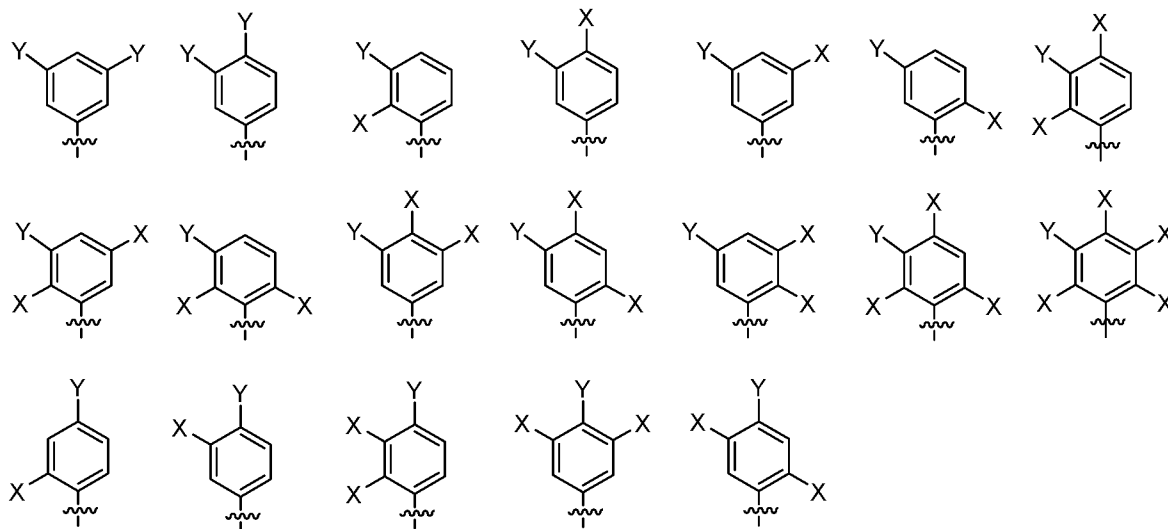




Y can be attached to positions 3, 4 or 5 or a combination of these

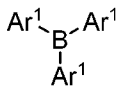
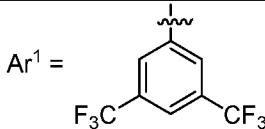
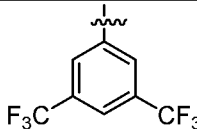
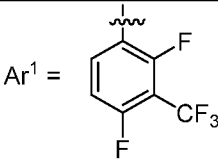
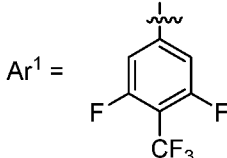
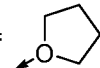
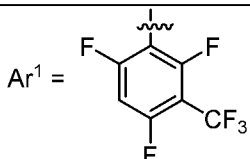
X can be attached to positions 2, 3, 4, 5 or 6 or a combination of these

[0029] Whereas each Ar^1 has the same structure. Exemplary structures for Ar^1 are the following, referred to as Set 1 structures:



[0030] According to exemplary embodiments, the Lewis acid catalyst is a boron based Lewis acid catalyst that has the general formula $\text{B}(\text{R}^1)_1(\text{R}^2)_1(\text{R}^3)_1(\text{R}^4)_{0\text{ or }1}$, whereas R^1 , R^2 , and R^3 are the fluoroalkyl-substituted phenyl group, and optionally R^4 is the functional group or functional polymer group. For example, the fluoroalkyl-substituted phenyl group is a 2,4-difluoro-3-(trifluoromethyl)phenyl group. For example, the fluoroalkyl-substituted phenyl group is a 2,4,6-trifluoro-3-(trifluoromethyl)phenyl group. In exemplary embodiments, at least one of R^1 or R^2 or R^3 is a 3,4- or 3,5-bis(fluoroalkyl)-substituted phenyl group (e.g., a 3,4 or 3,5-bis(trifluoromethyl)-substituted phenyl group). For example, R^4 is a cyclic ether having 3-10 carbon atoms.

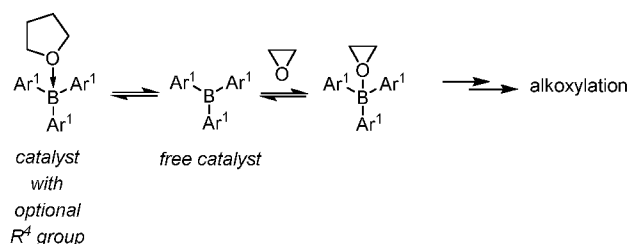
[0031] Exemplary structures for the Lewis acid catalysts, where M is Boron are shown below:

Basic Catalyst Structure $\text{Ar}^1 = \text{R}^1, \text{R}^2, \text{ or } \text{R}^3$ $\text{Ar}^2 = \text{R}^1, \text{R}^2, \text{ or } \text{R}^3$ $\text{Ar}^3 = \text{R}^1, \text{R}^2, \text{ or } \text{R}^3$ $\text{B} = \text{Boron}$	
Exemplary Structure 1	$\text{Ar}^1 =$ 
Exemplary Structure 2 (includes optional $\text{R} = \text{R}^4$)	$\text{Ar}^1 =$  $\text{R}^4 =$ 
Exemplary Structure 3 (includes optional $\text{R} = \text{R}^4$)	$\text{Ar}^1 =$  $\text{R}^4 =$ 
Exemplary Structure 4 (includes optional $\text{R} = \text{R}^4$)	$\text{Ar}^1 =$  $\text{R}^4 =$ 
Exemplary Structure 5 (includes optional $\text{R} = \text{R}^4$)	$\text{Ar}^1 =$  $\text{R}^4 =$ 

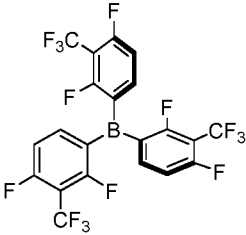
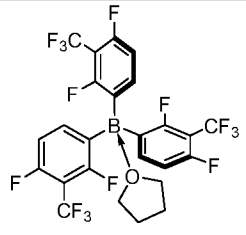
[0032] While the above illustrates exemplary structures that include boron, similar structures may be used that include other metals such as aluminum, indium, bismuth, and/or erbium.

[0033] Without intending to be bound by this theory, certain R^4 may help improve shelf life of the catalyst, e.g., without significantly compromising catalyst activity when utilized in a polymerization reaction. For example, the catalyst comprising M , R^1 , R^2 , and R^3 may be present in the form with the optional R^4 (form $\text{M}(\text{R}^1)_1(\text{R}^2)_1(\text{R}^3)_1(\text{R}^4)_1$) or without the optional R^4 (form $\text{M}(\text{R}^1)_1(\text{R}^2)_1(\text{R}^3)_1$). The optional R^4 may dissociate step-wise from $\text{M}(\text{R}^1)_1(\text{R}^2)_1(\text{R}^3)_1(\text{R}^4)_1$ to give free $\text{M}(\text{R}^1)_1(\text{R}^2)_1(\text{R}^3)_1$, as shown below for $\text{M} = \text{B}$, which free $\text{M}(\text{R}^1)_1(\text{R}^2)_1(\text{R}^3)_1$ may be a catalyst for an alkoxylation/polymerization process, and/or may dissociate from $\text{M}(\text{R}^1)_1(\text{R}^2)_1(\text{R}^3)_1(\text{R}^4)_1$ in a concerted or other single-step process with the alkylene oxide to give a catalyst for an alkoxylation/polymerization process.

[0034] For example, the catalyst including M, R¹, R², and R³ may be present in the form with and without the optional R⁴ group, as shown below.



[0035] The ability of the optional R⁴ group to protect the boron, aluminum, indium, bismuth and erbium center from inadvertent decomposition reactions may be related to the decrease in the accessible volume of the center. The accessible volume of the center is defined as the volume around the atom, such as boron atom, that is available for interaction with a small molecule like a solvent molecule.

Catalyst	Accessible volume of boron (%)
	25
	10

[0036] Suitable R⁴ groups that can help increase catalyst shelf stability, e.g., without compromising catalyst activity, include diethyl ether, cyclopentyl methyl ether, methyl *tertiary*-butyl ether, tetrahydrofuran, tetrahydropyran, 1,4-dioxane, acetone, methyl isopropyl ketone, isopropyl acetate, and isobutyl acetate.

[0037] The Lewis acid catalyst used in exemplary embodiments may be a blend catalyst that includes one or more Lewis acid catalyst (e.g., each having the general formula B(R¹)₁(R²)₁(R³)₁(R⁴)_{0 or 1}) and optionally at least one other catalyst (such as catalyst known the art for producing polyether polyols). The blend catalyst may optionally include other

catalysts, in which Lewis acid catalysts having the general formula account for at least 25 wt%, at least 50 wt%, at least 70 wt%, at least 75 wt%, at least 80 wt%, at least 85 wt%, at least 90 wt%, at least 95 wt%, at least 99 wt%, etc., of the total weight of the blend catalyst.

DMC Catalyst

[0038] The catalyst component may optionally include DMC catalysts. Exemplary DMC catalysts and method of producing DMC catalyst are described, e.g., in U.S. Patent Nos. 3,278,457, 3,278,458, 3,278,459, 3,404,109, 3,427,256, 3,427,334, 3,427,335, and 5,470,813. An exemplary type of DMC catalyst is a zinc hexacyanocobaltate catalyst complex. The mDMC catalyst complexes may be prepared using modified methods of forming the DMC catalysts. The DMC catalyst, e.g., ones that are known in the art, may be used in the catalyst system that includes the Lewis acid catalyst. The DMC catalyst may be the first or second catalyst that is provided.

[0039] For example, the DMC catalysts may be represented by the Formula 1:



wherein M and M³ are each metals; M¹ is a transition metal different from M. X¹ represents a group other than cyanide that coordinates with the M¹ ion. M² is a transition metal. X² represents a group other than cyanide that coordinates with the M² ion. X¹ or X² may each independently be a halogen, sulfate, nitrate, phosphate, carbonate, or chlorate. In exemplary embodiments, X¹ and X² are the same and are chloride. A¹ represents an anion; b, c and d are numbers that reflect an electrostatically neutral complex; r is from 4 to 6; t is from 0 to 2; x and y are integers that balance the charges in the metal salt M³_xA_y, and n is zero or a positive integer. For example, n is from 0.01 to 20. The foregoing formula does not reflect the presence of neutral complexing agents such as t-butanol which are often present in the DMC catalyst complex.

[0040] Referring to Formula (I), M and M³ each are a metal ion independently selected from (e.g., from the group consisting of): Zn²⁺, Fe²⁺, Co²⁺, Ni²⁺, Mo⁴⁺, Mo⁶⁺, Al³⁺, V⁴⁺, V⁵⁺, Sr²⁺, W⁴⁺, W⁶⁺, Mn²⁺, Sn²⁺, Sn⁴⁺, Pb²⁺, Cu²⁺, La³⁺ and Cr³⁺. Exemplary embodiments include at least Zn²⁺. Further, M¹ and M² each are a metal ion independently selected from (e.g., from the group consisting of): Fe³⁺, Fe²⁺, Co³⁺, Co²⁺, Cr²⁺, Cr³⁺, Mn²⁺, Mn³⁺, Ir³⁺, Ni²⁺, Rh³⁺, Ru²⁺, V⁴⁺, V⁵⁺, Ni²⁺, Pd²⁺, and Pt²⁺. Among the foregoing, those in the plus-three oxidation state may be used for the M¹ and M² metal. Exemplary embodiments include Co³⁺ and/or Fe³⁺.

[0041] Suitable anions A include, but are not limited to, halides such as chloride, bromide and iodide, nitrate, sulfate, carbonate, cyanide, oxalate, thiocyanate, isocyanate, perchlorate, isothiocyanate, an alkanesulfonate such as methanesulfonate, an arylenesulfonate such as p-toluenesulfonate, trifluoromethanesulfonate (triflate), and a C₁₋₄ carboxylate. Exemplary embodiments include the chloride ion.

[0042] Referring to Formula (I), r is an integer that is 4, 5 or 6. In exemplary embodiments, r is 4 or 6. Further, t is an integer from 0 to 2, and in exemplary embodiments t is 0. The sum of r + t may equal six.

[0043] In exemplary embodiments, the DMC catalyst is a zinc hexacyanocobaltate catalyst complex. The DMC catalyst may be complexed with t-butanol. The DMC catalyst used in exemplary embodiments may be a blend catalyst that includes of one or more DMC catalysts. The blend catalyst may optionally include a non-DMC catalyst, in which the DMC catalysts account for at least 75 wt% of the total weight of the blend catalyst. The blend catalyst may exclude any of Lewis acid catalyst that is added at a later time in the dual catalyst system.

Use of the Catalyst Component

[0044] In embodiments where the Lewis acid catalyst is used the alkoxylation of low hydroxyl equivalent weight starter compounds, also referred to as initiators, may proceed directly from the starter compound to a finished polyether polyol by the polymerization of one or more alkylene oxides. Further, the use of the Lewis acid catalyst during the polymerization reaction may reduce certain side reactions that lead to increased polydispersity and/or to increased acetal content in a final product.

[0045] The starter compound, also referred to as an initiator, has a low molecular weight such as less than 1,000 g/mol and a nominal hydroxyl functionality at least 2. The initiator is any organic compound that is to be alkoxyated in the polymerization reaction. The initiator may contain as many as 12 or more hydroxyl groups. For example, the initiator may be a diol or triol. Mixtures of starter compounds/initiators may be used. The initiator will have a hydroxyl equivalent weight less than that of the polyether product, e.g., may have a hydroxyl equivalent weight of less than 333 g/mol equivalence, less than 300 g/mol equivalence, from 30 to 300 g/mol equivalence, from 30 to 250 g/mol equivalence, from 50 to 250 g/mol equivalence, etc. Exemplary, initiator compounds include, but are not limited to, ethylene glycol, diethylene glycol, triethylene glycol, propylene glycol, dipropylene glycol, tripropylene glycol, 1,4-butane diol, 1,6-hexane diol, 1,8-octane diol,

cyclohexane dimethanol, glycerin, trimethylolpropane, trimethylolmethane, pentaerythritol, sorbitol, sucrose, as well as alkoxylates (especially ethoxylates and/or propoxylates) of any of these that have a number average molecular weight less than that of the product of the polymerization (e.g., less than 1000 g/mol).

[0046] The starter compound/initiator may be a low molecular weight polyether polyol that has been formed using an alkylene oxide such as propylene oxide, ethylene oxide, and/or butylene oxide (e.g., which is polymerized with another starter compound/initiator). The starter compound may be a diol or triol. For example, the starter compound is an all propylene oxide based diol or triol having a hydroxyl functional based equivalent weight of less than 333 g/mol equivalence and/or less than 300 g/mol equivalence. In another example, the starter compound is an all ethylene oxide based diol or triol having a hydroxyl functional based equivalent weight of less than 333 g/mol equivalence and/or less than 300 g/mol equivalence

[0047] When the Lewis acid catalyst is used the temperature of the reactor may be reduced at least 20 °C as compared to when the DMC catalyst is used. For example, the temperature for use of a DMC catalyst may be from 125 °C to 160 °C (e.g., during a time at which an alkylene oxide feed is gradually/slowly added to the reactor and after the time at which the starter compound is mixed with the DMC catalyst). The temperature for use of the Lewis acid catalyst may be from 25 °C to 115 °C and/or from 60 °C to 115 °C (e.g., during a time at which ethylene oxide is fed to the reactor to form an EO-capped polyol). In exemplary embodiments, the control of the relative contribution of a mixture containing an active DMC catalyst and an active Lewis acid may enable the Lewis acid to dominate the addition of alkylene oxide onto chain ends.

[0048] In an exemplary embodiment, when the polyether polyol is derived from propylene oxide based initiator (e.g., a polyoxypropylene starter compound), during the polymerization process ethylene oxide may be added to the reaction mixture to form the polyether polyol having a number average molecular weight of greater than the number average molecular weight of the initiator.

[0049] The polymerization reaction can be performed in any type of vessel that is suitable for the pressures and temperatures encountered. In a continuous or semi-continuous process the vessel may have one or more inlets through which the alkylene oxide and additional initiator compound may be introduced during the reaction. In a continuous process, the reactor vessel should contain at least one outlet through which a

portion of the partially polymerized reaction mixture may be withdrawn. A tubular reactor that has single or multiple points for injecting the starting materials, a loop reactor, and a continuous stirred tank reactor (CSTR) are all suitable types of vessels for continuous or semi-continuous operations. An exemplary process is discussed in U.S. Patent Publication No. 2011/0105802.

[0050] The resultant polyether polyol product may be further treated, e.g., in a flashing process and/or stripping process. For example, the polyether polyol may be treated to reduce catalyst residues even though the catalyst residue may be retained in the product. Moisture may be removed by stripping the polyol. The polyether polyol derived from ethylene oxide, according to embodiments, may have a Lewis acid catalyst concentration (in ppm in the final polyol) of from 50 ppm to 1000 ppm (e.g., 100 ppm to 500 ppm and/or 100 ppm to 250 ppm).

[0051] The polymerization reaction may be characterized by the "build ratio", which is defined as the ratio of the number average molecular weight of the polyether product to that of the initiator compound. This build ratio may be as high as 160, but is more commonly in the range of from 2.5 to about 65 and still more commonly in the range of from 2.5 to about 50. The build ratio is typically in the range of from about 2.5 to about 15, or from about 7 to about 11 when the polyether product has a hydroxyl equivalent weight of from 85 to 400.

[0052] Exemplary embodiments relate to preparing the polyether polyols using one or more of certain Lewis acid catalysts as polymerization catalysts that may achieve a lower acetal content in the resultant polyether polyols (e.g., less than 5.0 mol%, less than 4.0 mol%, less than 3.0 mol%, less than 1.5 mol%, less than 1.0 mol%, less than 0.8 mol%, less than 0.5 mol%, less than 0.2 mol% etc.), based on the total moles of carbon in the resultant polyol chains, while still producing high molecular weight polyols (e.g., poly-ethylene oxide polyols, poly-propylene oxide/ethylene oxide polyols, poly-ethylene oxide/butylene oxide polyols, etc.)

[0053] Exemplary embodiments related to preparing EO-capped polyether polyols at a high yield, e.g., a yield of at least 50 wt%, at least 60 wt%, at least 70 wt%, at least 80 wt%, at least 90 wt%, at least 95 wt%, etc., based on a total weight of the resultant polyol product.

[0054] Exemplary embodiments relate to using one or more of certain Lewis acid catalyst as polymerization catalyst, such that use of the Lewis acid catalyst may result in higher activation barriers to aldehyde formation, which is an undesired product, as

compared to the activation barrier for forming the desired polyether polyol product or intermediate. As such the formation of the desired product or intermediate product may be favored during the polymerization process compared to the undesired products. For example, the activation barrier to aldehyde formation may be greater than 6.0 kcal/mol, greater than 7.0 kcal/mol, greater than 8.0 kcal/mol, and/or greater than 9.0 kcal/mol. The activation barrier to aldehyde formation may be less than 30 kcal/mol and/or less than 20 kcal/mol.

[0055] Polyether polyols produced in accordance with embodiments may be useful for making polyurethanes. The polyurethane polymers may be prepared as the reaction product of the polyether polyol and an isocyanate (such as a polyisocyanate, of which examples include methylenediphenyl diisocyanate also known as MDI and toluene diisocyanate also known as TDI). For example, higher equivalent weight polyether polyol products may be useful in making elastomeric or semi-elastomeric polyurethane products, including noncellular or microcellular elastomers, coatings, adhesives, sealants, composites, and flexible, rigid, and viscoelastic polyurethane foams. The polyurethane foams may be made in a slabstock or molding process.

[0056] All parts and percentages are by weight unless otherwise indicated. All molecular weight values are based on number average molecular weight unless otherwise indicated.

Examples

[0057] Approximate properties, characters, parameters, etc., are provided below with respect to various working examples, comparative examples, and the materials used in the working and comparative examples.

Catalyst Synthesis

[0058] The general production for catalyst synthesis is as follows. Unless otherwise noted, all experimental procedures and manipulations of chemical substances are performed in a nitrogen-purged glove box or on a Schlenk line. All bulk reaction solvents (toluene, diethyl ether, hexane, tetrahydrofuran (THF)) are dried by passage through columns of alumina and Q5 reactive scavenger. All other solvents are purchased from Aldrich anhydrous grade and stored over activated 3 Å molecular sieves prior to use. NMR solvents (CDCl_3 and C_6D_6), obtained from Cambridge Isotope Laboratories, Inc., are dried over molecular sieves or, in the case of C_6D_6 , dried using Na/K alloy. Further, 1-bromo-3,5-bis(trifluoromethyl)benzene, 1-bromo-2,4-difluoro-3-trifluoromethylbenzene, and 1-bromo-

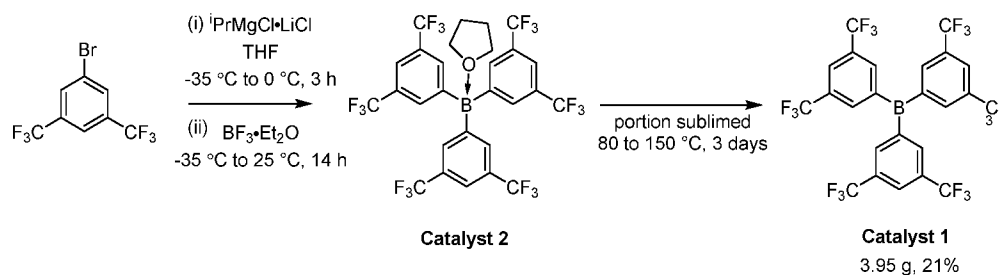
3,5-difluoro-4-trimethylbenzene are purchased from Oakwood Chemical. Also, 1-bromo-2,4,6-trifluoro-3-trifluoromethylbenzene, isopropylmagnesium chloride-lithium chloride (solution in THF), and boron trifluoride diethyletherate are obtained from Sigma-Aldrich and used as received. Further, isopropylmagnesium chloride lithium chloride complex (solution in THF) is titrated before use using 1.00 M decanol in toluene with 1,10-phenanthroline as an indicator.

[0059] Multinuclear NMR spectra (^1H , ^{13}C , ^{19}F) are collected on one of the following instruments: Varian MR-400 or Varian VNMR-500. The ^1H and ^{13}C NMR chemical shifts are referenced in parts per million relative to residual solvent peaks: ^1H – 7.15 ppm for C_6D_6 , 7.25 ppm for CDCl_3 ; ^{13}C – 128.00 ppm for C_6D_6 , and 77.00 ppm for CDCl_3 . Boron-11 NMR chemical shifts are referenced externally to $\text{BF}_3(\text{Et}_2\text{O})$ (0 ppm), and ^{19}F NMR chemical shifts are referenced externally to CFCl_3 (0 ppm). Sub-ambient reaction temperatures, except when dry ice or ice were the sole means of cooling, are measured using an Extech Instruments EasyView™10 Dual K model EA 10 thermometer with a fine JKEM sensor PTFE wire K 36INJ.

[0060] **Catalyst 1** is (tris(3,5-bis(trifluoromethyl)phenyl)borane).

[0061] **Catalyst 2**, is the THF adduct of **Catalyst 1**.

[0062] **Catalyst 1** and **2** are prepared according to the following Schematic 2:

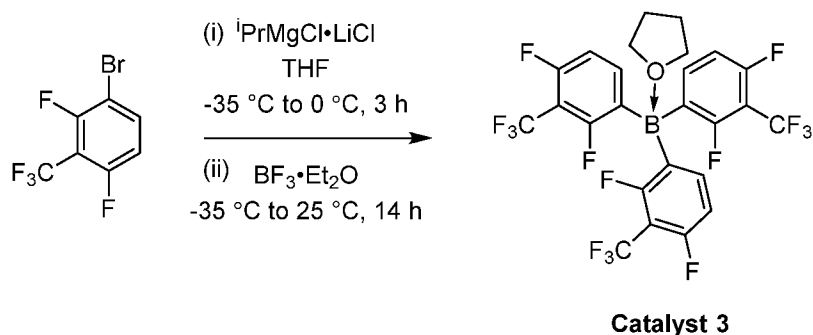


Schematic 2

[0063] In particular, isopropylmagnesium chloride-lithium chloride (70.8 mL, 87.0 mmol, 1.23 M solution in THF) is added to a solution of 1-bromo-3,5-bis(trifluoromethyl)benzene (25.5 g, 87.0 mmol) in THF (250 mL) which is in an acetone bath cooled with dry ice and held within a temperature range of between -35 °C to -25 °C during the addition. After the addition is complete, the reaction flask is transferred to an ice bath (0 °C) and the reaction mixture is stirred for 3 hours. The reaction mixture is cooled to about -35 °C and boron trifluoride diethyletherate (4.26 mL, 29.0 mmol) is added while maintaining the reaction mixture at a temperature range of between -35 °C to -25 °C. The

reaction mixture is allowed to warm to room temperature while it is stirred overnight. The resultant ^{19}F NMR spectra of the reaction mixture shows a major peak (95%) at δ -63.2 and a minor peak (5%) at δ -63.7 corresponding to 1-bromo-3,5-bis(trifluoromethyl)benzene. Next, the THF is removed from the reaction mixture under reduced pressure. The residue is extracted with toluene and filtered using several PTFE frits because the very fine precipitate may be difficult to filter. The volatiles are removed under reduced pressure to give a very viscous oil. A portion of the product (about 2/3 to 3/4) is put in a sublimator and sublimed (by starting at 80 °C and gradually increasing the temperature to 150 °C over several days in an oil bath under ≤ 1 mtorr vacuum) to give 3.95 grams (6.07 mmol, 21%) of white solid on the sublimator finger. Small crystals may also be present. This material is characterized by multinuclear NMR spectroscopy as Catalyst 1. Additional, less pure, product is scraped out of the top portion of the sublimator body, in an amount of 2.01 grams. The less pure material, which by NMR is characterized as a 2:1 mixture of borane to THF, is dissolved in THF, filtered, and the volatiles are removed under reduced pressure. This material is characterized by multinuclear NMR spectroscopy as Catalyst 2 (2.00 g, 2.77 mmol, 9.5 %) Total yield: 6.07 mmol Catalyst 1 and 2.77 mmol Catalyst 2 (30 % overall yield).

[0064] Catalyst 3 is the THF adduct of tris(2,4-difluoro-3-(trifluoromethyl)phenyl)borane and is prepared according to Schematic 3:

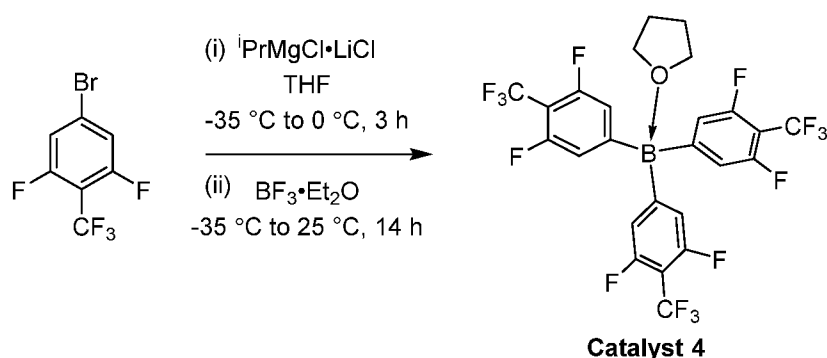


Schematic 3

[0065] In particular, isopropylmagnesium chloride-lithium chloride (15.6 mL, 19.2 mmol, 1.23 M solution in THF) is added to a solution of 1-bromo-2,4-difluoro-3-trifluoromethyl-benzene (5.00 g, 19.2 mmol) in THF (100 mL) which is in an acetone bath cooled with dry ice and held within a temperature range of between -35 °C to -25 °C during the addition. After the addition is complete, the reaction flask is transferred to an ice bath (0 °C) and the reaction mixture is stirred for 3 hours. The reaction mixture is cooled to

about -35 °C and boron trifluoride diethyletherate (0.79 mL, 6.4 mmol) is added while maintaining the reaction mixture at a temperature range of between -35 °C to -25 °C. The reaction mixture is allowed to warm to room temperature while it is stirred overnight. Next, the THF is removed from the reaction mixture under reduced pressure. The residue is extracted with toluene and filtered using a PTFE frit. The volatiles are removed from the filtrate under reduced pressure to give the product, the THF adduct of tris(2,4-difluoro-3-(trifluoromethyl)phenyl)borane.

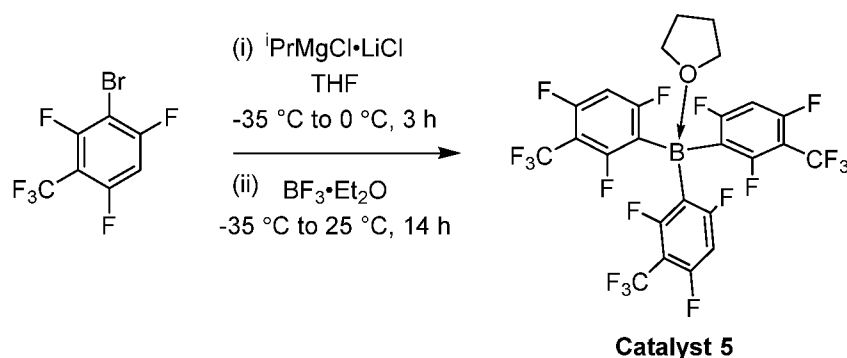
[0066] **Catalyst 4** is the THF adduct of tris(3,5-difluoro-4-(trifluoromethyl)phenyl)borane and is prepared according to Schematic 4:



Schematic 4

[0067] In particular, isopropylmagnesium chloride-lithium chloride (31.1 mL, 38.3 mmol, 1.23 M solution in THF) is added to a solution of 1-bromo-3,5-difluoro-4-trifluoromethylbenzene (10.0 g, 38.3 mmol) in THF (150 mL) which is in an acetone bath cooled with dry ice and held within a temperature range of between -35 °C to -25 °C during the addition. After the addition is complete, the reaction flask is transferred to an ice bath (0 °C) and the reaction mixture is stirred for 3 hours. The reaction mixture is cooled to about -35 °C and boron trifluoride diethyletherate (1.58 mL, 12.8 mmol) is added while maintaining the reaction mixture at a temperature range of between -35 °C to -25 °C. The reaction mixture is allowed to warm to room temperature while it is stirred overnight. Next, the THF is removed from the reaction mixture under reduced pressure. The residue is extracted with toluene and filtered using a PTFE frit. The volatiles are removed from the filtrate under reduced pressure to give the product, the THF adduct of tris(3,5-difluoro-4-(trifluoromethyl)phenyl)borane.

[0068] **Catalyst 5** is the THF adduct of tris(2,4,6-trifluoro-3-(trifluoromethyl)phenyl)borane and is prepared according to Schematic 5:



Schematic 5

[0069] In particular, isopropylmagnesium chloride-lithium chloride (5.9 mL, 7.3 mmol, 1.23 M solution in THF) is added to a solution of 1-bromo-2,4,6-trifluoro-3-trifluoromethylbenzene (2.00 g, 7.17 mmol) in THF (50 mL) which is in an acetone bath cooled with dry ice and held within a temperature range of between -35 °C to -25 °C during the addition. After the addition is complete, the reaction flask is transferred to an ice bath (0 °C) and the reaction mixture is stirred for 3 hours. The reaction mixture is cooled to about -35 °C and boron trifluoride diethyletherate (0.30 mL, 2.4 mmol) is added while maintaining the reaction mixture at a temperature range of between -35 °C to -25 °C. The reaction mixture is allowed to warm to room temperature while it is stirred overnight. Next, the THF is removed from the reaction mixture under reduced pressure. The residue is extracted with toluene and filtered using a PTFE frit. The volatiles are removed from the filtrate under reduced pressure to give the product, the THF adduct of tris(2,4,6-trifluoro-3-(trifluoromethyl)phenyl)borane.

[0070] **Catalyst A** is tris(pentafluorophenyl)borane, also referred to as FAB (available from Boulder Scientific).

[0071] **Catalyst B** is a zinc hexacyanocobaltate catalyst complex (available from Covestro under the name Arcol 3® Catalyst).

Preparation of Polyols

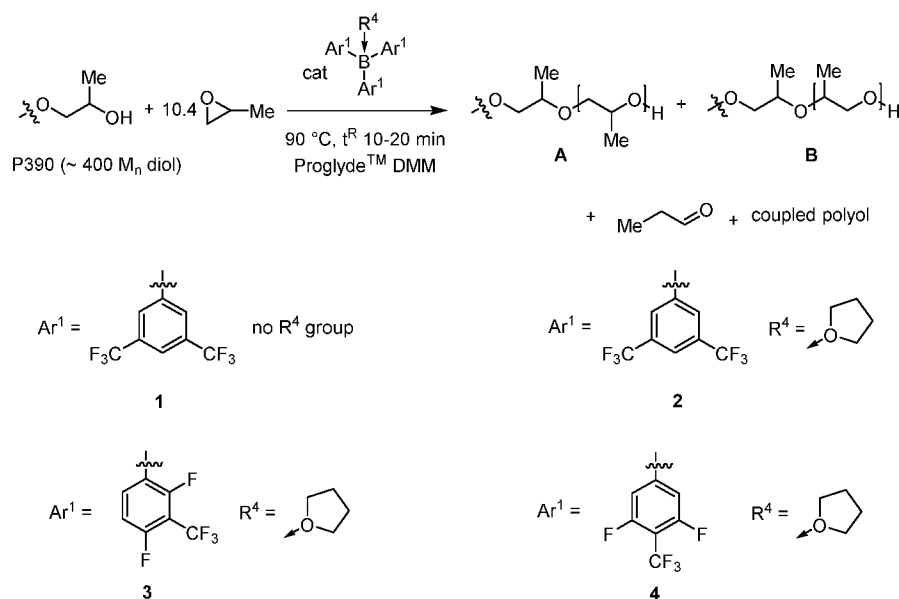
[0072] For preparing the polyols, the following materials are principally used:

P390

A starter compound that is a polyoxypropylene diol having a number average molecular weight of approximately 390 g/mol (available from The Dow Chemical Company as VORANOL™ P 390).

Solvent	A glycol diether that has no hydroxyl functionality (available from The Dow Chemical Company as PROGLYDE™ DMM).
Additive	An acidifying agent that includes phosphoric acid.

[0073] In particular, the following reaction may be carried out in a continuous flow reactor using Catalysts 1 to 5 as discussed above. The reactions may be carried out in a manner shown below in exemplary Schematic 6, and in view of the conditions provided in Table 1:



Schematic 6

[0074] The polyols of Working Examples 1 to 5 and Comparative Examples B and C may be prepared using P390 as the initiator, ethylene oxide (EO) as the monomer, and the Solvent according to the conditions outlined in Table 1, below. Referring to Table 1, the EO binding enthalpy, and activation barrier to aldehyde are determined according to the computational methods discussed below.

Table 1

	Catalyst	Catalyst Con. (ppm)	Time (Min)	Temp (°C)	EO binding enthalpy (kcal/mol)	Activation barrier to aldehyde (kcal/mol)
Ex. A	-	-	10	90	n/a	n/a
Ex. B	A	1000	10	90	-6.0	5.3
Ex. C			20			
Ex. 1	1	1000	10	90	-3.7	8.7
Ex. 2			20			
Ex. 3	2	1000	10	90		
Ex. 4	3	1000	10	90	-5.7	6.2
Ex. 5	4	1000	10	90	-6.8	9.9

[0075] Comparative Example A is a negative control that may be run without catalyst. This example may be carried out by mixing the initiator and ethylene oxide in the tubular reactor at 90 °C for 10 min.

[0076] The polyol samples for Working Examples 1 to 5 and Comparative Examples B and C, may be prepared in a continuous flow reactor that is a microreactor available from Vapourtec Inc. can be used. For the examples, neat EO monomer is fed to a pump via a pressure cylinder at 50 psig. A solvent reservoir containing the Solvent is connected to another pump. A 2 mL injection loop is utilized to introduce a solution of the specified catalyst and initiator (as 60 wt % of P390 in dipropylene glycol dimethyl ether) into the system. By controlling the flow rate, the catalyst and starter may be introduced into the flow system at a defined rate. The EO monomer and initiator-catalyst-Solvent solution are combined at a mixing unit and fed into a 2 mL stainless steel coiled reactor. A back pressure regulator set at 250 psig is used to control the system pressure and assist the EO to remain in a liquid phase. The continuous pressure reactor is charged with 0.1 mL/min of the initiator-catalyst-Solvent mixture. The ethylene oxide is fed to the reactor at a constant feed rate of 0.1 mL/min. Once the initiator-catalyst-Solvent mixture is introduced into the sample loop, the first 5.13 mL of the product mixture is diverted to a scrubber consisting of 3 wt % aqueous potassium hydroxide. The next 3.04 mL of product mixture is collected and analyzed by MALDI spectrometry.

[0077] The Temperature in Table 1 is the temperature in the reactor. The Time is residence time, which is defined as follows:

$$\text{residence time} = \frac{\text{reactor volume}}{(\text{flow rate of pump A} + \text{flow rate of pump B})}$$

When the flow rates of pumps A and B are 0.1 mL/min,

$$\text{residence time} = \frac{2 \text{ mL}}{(0.1 + 0.1) \text{ mL/min}} = 10 \text{ min}$$

When the flow rates of pumps A and B are 0.05 mL/min,

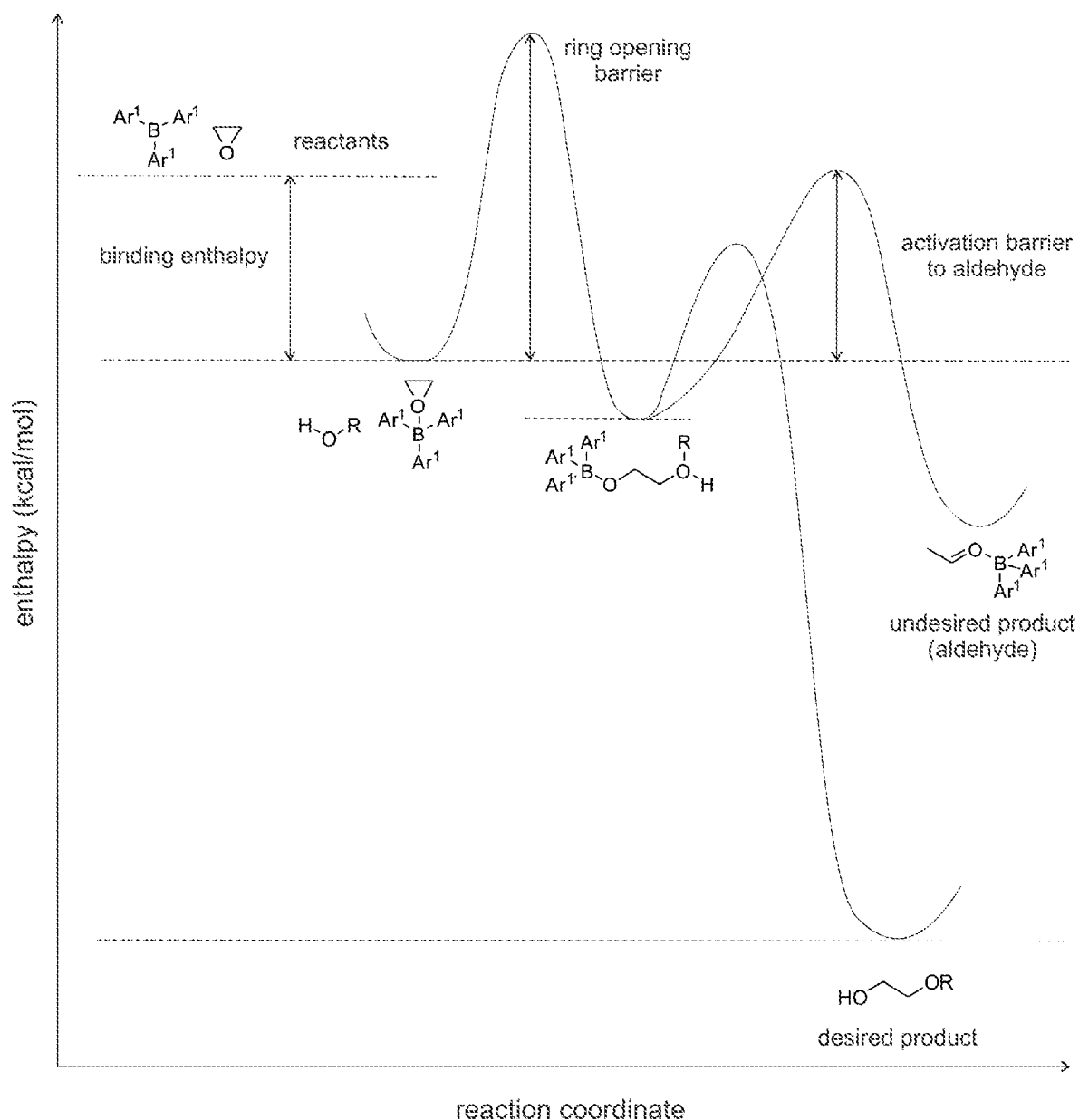
$$\text{residence time} = \frac{2 \text{ mL}}{(0.05 + 0.05) \text{ mL/min}} = 20 \text{ min}$$

[0078] The number-average molecular weight (Mn) achieved in the polymerization reaction may depend on the amount of volatile side-products (e.g. acetaldehyde) formed. For example, higher levels of volatile side-products may result in a Mn that is significantly lower than the theoretical Mn. Conversely, low levels of volatile side-products may help achieve a Mn that is close to the theoretical Mn. It may be desirable to achieve a Mn that is close to the theoretical Mn.

[0079] The PDI is defined as the ratio of the weight-average molecular weight (Mw) to the number-average molecular weight (Mn). The PDI may represent a measure of the extent of acetal coupling, as this reaction may effectively double the molecular weight. Accordingly, a comparison of the PDI at similar Mn values may provide a measure of the selectivity of a catalyst for alkoxylation (intended reaction) versus isomerization and acetalization. Lower PDI may be preferable for higher chemoselectivity.

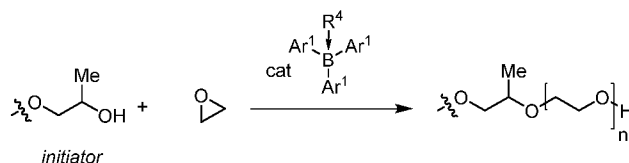
[0080] The EO binding enthalpy is calculated relative to a resting state consisting of the free catalyst (where R⁴ is not present) and EO. Favorable binding (higher negative values, for example greater than -3.0 kcal/mol, greater than -5.0 kcal/mol, etc) is preferable for higher activity. Referring to Table 1, it is seen that calculations on Catalysts 1 to 4 provide a favorable EO binding enthalpy such that favorable activity is realized. Another measure of activity is the ring opening barrier shown below. Lower ring opening barriers are preferable for higher activity.

[0081] The activation barrier to aldehydes determines the amount of aldehyde and acetal formed, as shown below. Higher activation barriers are preferable for lower levels of aldehyde and subsequent acetal formation.



[0082] Referring to Working Examples 1 to 5 and Comparative Examples B and C, it is found that the activation barrier to undesired products (in comparison to the activation barrier for the desired EO content polyether polyol) is significantly higher for Catalysts 1 to 4 compared to Catalyst A. As such, it is unexpectedly found that the structures of Catalysts 1 to 4 may allow for increased yield of the desired product, as compared to Catalyst A.

[0083] Additional, Working Example 6 and Comparative Example D are carried out in a semi-batch process using P390 initiator and ethylene oxide monomer, using Catalyst 2 or Catalyst A, and in view of conditions provided in Table 2 and according to Schematic 7:



Schematic 7

[0084] Referring to Table 2, Init refers to the initiator used, Mon refers to the monomer used, and M/I refers to the ratio of the monomer to initiator used. The monomer used is ethylene oxide (EO).

Table 2

	Init	Mon	M/I ratio	Catalyst	Catalyst Con. (ppm)	Temp (°C)	Mn	PDI	Yield (%)
Ex. D	P390	EO	10	A	500	55	888	1.49	79
Ex. 6	P390	EO	10	2	500	55	1039	1.34	88

[0085] For the semi-batch alkoxylation reactions, the initiator was dried and charged into the pressure reactor using one of three procedures.

[0086] Procedure A: The initiator was charged directly to the Parr reactor via a funnel. Drying was performed in the reactor for 180 min at 140 °C under a nitrogen purge.

[0087] Comparative Example D (Table 2): A 600 mL pressure reactor is charged with 55.2 grams of VORANOL™ P390, a poly(propylene oxide) triol of number-average molecular weight 400, using Procedure A. A solution of catalyst A (70 mg) in anhydrous tetrahydrofuran (2 mL) is added in one portion through a sample addition port under a nitrogen purge. After purging for 5 min, the nitrogen purge is stopped and the reactor vent is closed. Nitrogen is added through the reactor inlet to inert the headspace. Ethylene oxide (84.3 g) is added to the reactor at a reaction temperature of 55 °C and a constant feed rate of 0.75 g/min. Upon completion of ethylene oxide feed, the reaction mixture is allowed to digest for 50 min at 55 °C. The reactor is vented and the reaction mixture is heated to 90 °C and purged for 30 minutes. The reaction mixture is cooled to 60 °C and the product is collected (111.1 g, 79%). Number-average molecular weight = 888 (by gel permeation chromatography); Polydispersity index (PDI) = 1.49 (by gel permeation chromatography).

[0088] Working Example 6 (Table 2): A 500 mL pressure reactor is charged with 60.0 grams of VORANOL™ P390, a poly(propylene oxide) triol of number-average molecular weight 400, using Procedure A. A solution of Catalyst 2 (75 mg) in anhydrous tetrahydrofuran (2 mL) is added in one portion through a sample addition port under a

nitrogen purge. After purging for 5 min, the nitrogen purge is stopped and the reactor vent is closed. Nitrogen is added through the reactor inlet to inert the headspace. Ethylene oxide (99.2 g) is added to the reactor at a reaction temperature of 55 °C and a constant feed rate of 0.75 g/min. Upon completion of ethylene oxide feed, the reaction mixture is allowed to digest for 50 min at 55 °C. The reactor is vented and the reaction mixture is heated to 90 °C and purged for 30 minutes. The reaction mixture is cooled to 60 °C and the product is collected (139.4 g, 88%). Number-average molecular weight = 1039 (by gel permeation chromatography); Polydispersity index (PDI) = 1.34 (by gel permeation chromatography).

[0089] For Working Example 6 and Comparative Example D, the percent of yield of the desired product in the resultant polyol samples is measured (based on a total moles of the resultant polyol samples). Referring to Table 2, it is seen that the moles of yield of the desired product is higher when using Catalyst 2, as compared to Catalyst A.

[0090] A process for the preparation of a polyether polyol may be carried out in a continuous or semi-batch process using a sequential dual catalyst process, similar to International Publication No. WO 2016/064698, which is incorporated by reference.

[0091] Working Example 7: A 500 mL pressure reactor is charged with 60.0 grams of VORANOL™ P390, a poly(propylene oxide) triol of number-average molecular weight 400, using Procedure A. A solution of Catalyst 3 (75 mg) in anhydrous tetrahydrofuran (2 mL) is added in one portion through a sample addition port under a nitrogen purge. After purging for 5 min, the nitrogen purge is stopped and the reactor vent is closed. Nitrogen is added through the reactor inlet to inert the headspace. Ethylene oxide (90 g) is added to the reactor at a reaction temperature of 55 °C and a constant feed rate of 0.75 g/min. Upon completion of ethylene oxide feed, the reaction mixture is allowed to digest for 50 min at 55 °C. The reactor is vented and the reaction mixture is heated to 90 °C and purged for 30 minutes. The reaction mixture is cooled to 60 °C and the product is collected.

[0092] Working Example 8: A 500 mL pressure reactor is charged with 60.0 grams of VORANOL™ P390, a poly(propylene oxide) triol of number-average molecular weight 400, using Procedure A. A solution of Catalyst 4 (75 mg) in anhydrous tetrahydrofuran (2 mL) is added in one portion through a sample addition port under a nitrogen purge. After purging for 5 min, the nitrogen purge is stopped and the reactor vent is closed. Nitrogen is added through the reactor inlet to inert the headspace. Ethylene oxide (90 g) is added to the reactor at a reaction temperature of 55 °C and a constant feed rate of 0.75 g/min. Upon completion of ethylene oxide feed, the reaction mixture is allowed to digest for 50 min at 55

°C. The reactor is vented and the reaction mixture is heated to 90 °C and purged for 30 minutes. The reaction mixture is cooled to 60 °C and the product is collected.

[0093] Working Example 9: A 500 mL pressure reactor is charged with 60.0 grams of VORANOL™ P390, a poly(propylene oxide) triol of number-average molecular weight 400, using Procedure A. A solution of Catalyst 5 (75 mg) in anhydrous tetrahydrofuran (2 mL) is added in one portion through a sample addition port under a nitrogen purge. After purging for 5 min, the nitrogen purge is stopped and the reactor vent is closed. Nitrogen is added through the reactor inlet to inert the headspace. Ethylene oxide (90 g) is added to the reactor at a reaction temperature of 55 °C and a constant feed rate of 0.75 g/min. Upon completion of ethylene oxide feed, the reaction mixture is allowed to digest for 50 min at 55 °C. The reactor is vented and the reaction mixture is heated to 90 °C and purged for 30 minutes. The reaction mixture is cooled to 60 °C and the product is collected.

[0094] The analytical methods used with respect to the examples are described below:

[0095] *Determination of M_n for semibatch products:* Gel Permeation Chromatography (GPC) analysis is used for determination of number average molecular weight (M_n), which is carried out at a flow rate of 1.0 mL/min using four PLgel organic GPC columns connected in series (3 μ m, Agilent Inc.) and tetrahydrofuran as eluent. The column temperature is 40 °C. VORANOL™ CP 6001, VORANOL™ 210, 230-660, and 230-056N are used as standards.

[0096] *Percent yield determination of semibatch reaction:*

$$\text{yield (\%)} = \frac{\text{weight of product after purging with nitrogen at 90 °C for 30 min}}{\text{theoretical weight of product based on } \frac{M}{I} \text{ ratio}} \times 100$$

[0097] *Computational Methodology for determination of binding enthalpy and activation barrier to aldehyde:* The structures of species in ground and transition states are optimized using Density Functional Theory (DFT) at B3LYP/6-31g** level. The effect of dielectric medium is included by using conductor like polarizable continuum model (CPCM), where diethylether ($\epsilon = 4.2$) is used as the medium of choice. The vibrational analysis on the ground state geometries is performed and the lack of imaginary frequencies is used to ascertain the minima in the potential energy surface (PES). On the other hand, the same analysis on the transition state geometries indicated one imaginary frequency. In the latter case, the GaussView program is used to visualize the vibrational mode with imaginary frequency in order to ensure that the atoms moved along the desired reaction coordinate. For both ground-state and transition state geometries, the vibrational analysis is

used to compute the enthalpy (H_{298}) at 298 K by augmenting zero point energy to the electronic energy. For both ground state and transition state, various conformations were explored and the enthalpy of the lowest conformation was used to calculate binding and the barrier height for aldehyde formation. These calculations were performed using G09 suit of programs.

[0098] *Computational determination of free (or accessible) volume:* Once the optimized geometry of free catalysts (where the catalyst is not bound to the optional R^4 Lewis base) or coordinated complexes (where a catalyst is bound to the optional R^4 Lewis base) are obtained using the above method, a sphere of radius 3.0 Å is placed around the B atom (the volume of this sphere is denoted as V_1). This is followed by placing spheres on other atoms; the radii of these spheres are chosen to be the van der Waals radii of respective atoms. The volume of the sphere centered on B which is occluded by spheres on other atoms is computed using a Monte Carlo integration technique. The occluded volume is represented as V_2 . The free volume (FV) is calculated using the following equation:

$$FV = 1 - (V_2/V_1)$$

The FV descriptor varies between 0 and 1. This technique is implemented using Pipeline Pilot tool kit. This procedure is used in literature to understand bond dissociation trends.

Listing of the Claims:

1. A method of producing a polyether polyol, comprising:
reacting a low molecular weight initiator with ethylene oxide in the presence of a polymerization catalyst, the low molecular weight initiator having a nominal hydroxyl functionality of at least 2, and the polymerization catalyst being a Lewis acid catalyst having the general formula $M(R^1)_1(R^2)_1(R^3)_1(R^4)_{0 \text{ or } 1}$, whereas M is boron, R^1 , R^2 and R^3 each is a fluoro/chloro-fluoroalkyl-substituted phenyl group, difluoro/chloro-fluoroalkyl-substituted phenyl group, trifluoro/chloro-fluoroalkyl-substituted phenyl group, or tetrafluoro/chloro-fluoroalkyl-substituted phenyl group, and optional R^4 includes a functional group or functional polymer group, said functional group or functional group polymer being a molecule that contains at least one of the following: water, an alcohol, an alkoxy, a ketone, an ester, an organosiloxane, an amine, a phosphine, an oxime, and substituted analogs thereof; and
forming a polyether polyol having a number average molecular weight of greater than the number average molecular weight of the low molecular weight initiator in the presence of the Lewis acid catalyst.

2. A method of producing a polyether polyol, comprising:
reacting a low molecular weight initiator with ethylene oxide in the presence of a polymerization catalyst, the low molecular weight initiator having a nominal hydroxyl functionality of at least 2, and the polymerization catalyst being a Lewis acid catalyst having the general formula $M(R^1)_1(R^2)_1(R^3)_1(R^4)_1$, whereas M is boron, aluminum, indium, bismuth or erbium, R^1 , R^2 and R^3 each includes a same fluoroalkyl-substituted phenyl group, and R^4 includes a functional group or functional polymer group, said functional group or functional group polymer being a molecule that contains at least one of the following: water, an alcohol, an alkoxy, a ketone, an ester, an organosiloxane, an amine, a phosphine, an oxime, and substituted analogs thereof; and
forming a polyether polyol having a number average molecular weight of greater than the number average molecular weight of the low molecular weight initiator in the presence of the Lewis acid catalyst.

3. The method as claimed in claim 2, wherein the Lewis acid catalyst has the general formula $M(R^1)_1(R^2)_1(R^3)_1(R^4)_1$, whereas M is boron, and each of R^1 , R^2 , and R^3 is a 3,4- or 3,5-bis(fluoroalkyl)-substituted phenyl group.

4. The method as claimed in claim 2, wherein R^4 is a cyclic ether having 3-10 carbon atoms.

5. The method as claimed in claim 2, wherein R^4 is a ketone having 3-10 carbon atoms.

6. The method as claimed in any one of claims 1 to 5, wherein the polyether polyol has a yield of at least 60% based on actual yield of an ethylene oxide capped polyol and a theoretical yield of the ethylene oxide capped polyol.

7. The method as claimed in any one of claims 1 to 6, wherein the low molecular weight initiator is a polyether diol or triol derived from at least one selected from propylene oxide, ethylene oxide, and butylene oxide.

8. A method of producing a polyurethane product, the method comprising:
providing a polyether polyol produced according to the method as claimed in any one of claims 1 to 7, and
providing an isocyanate.