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Cyclic Guanidines as Efficient Organocatalysts for the Synthesis of Polyurethanes

Jérome Alsarraf,[†,‡] Yacine Ait Ammar,[†,‡,§] Frédéric Robert,[†,‡] Eric Cloutet,[§,⊥] Henri Cramail,*[,§,⊥] and Yannick Landais*[,†,‡]

[†]Univ. Bordeaux, ISM, UMR 5255, 33400 Talence, France

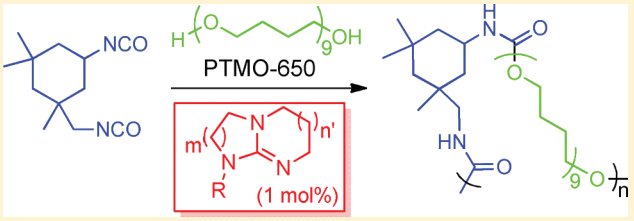
[‡]CNRS, ISM, UMR 5255, 33400 Talence, France

[§]Univ. Bordeaux, LCPO, UMR 5629, 33600 Pessac, France

[⊥]CNRS, LCPO, UMR 5629, 33600 Pessac, France

Supporting Information

ABSTRACT: A systematic survey of basic/nucleophilic organocatalysts for the polyaddition in bulk of polyols, PEG-600, and PTMO-650, to isophorone diisocyanate (IPDI) has been performed. Guanidines were shown to be very efficient catalysts for the urethane linkage formation. Bicyclic penta-alkylated guanidines such as MTBD led to polyurethane molecular weight and dispersity that are in the range of those observed with tin-based catalysts such as DBTDL. Tetra-alkylated guanidine such as TBD was shown to be a weaker catalyst as compared to pentaalkylated guanidines, as a result of its high reactivity toward isocyanate, resulting in the formation of a less nucleophilic urea. Although the mechanism has not yet been firmly established, these experiments suggest that a nucleophilic-catalysis mechanism, involving the attack of one of the nitrogen of the guanidine onto the unsaturated system of the isocyanate, should not be totally ruled out with such strong Brönsted base catalysts.



INTRODUCTION

Polyurethanes constitute an important class of polymeric materials, estimated around 5 wt % of the current world polymer production[1] with numerous technical applications (foams, coatings, biomaterials, fibers, etc.). Polyurethanes are usually prepared, based on the original discovery of Bayer[2] by the most straightforward route involving the addition of polyols to polyisocyanates in the presence of a catalyst. Organometallic reagents or tertiary amines are commonly employed to mediate this polyaddition. Dibutyltin dilaurate (DBTDL) is the most active catalyst currently in use,[3] but environmental concerns should lead, in not too distant a future, to a ban of such toxic organometallic reagents.[4] The presence of heavy metals in the resulting polymer also has detrimental effects on the aging of the final material. Recent efforts in polymer synthesis have thus focused on the design of organocatalysts that could advantageously replace metal-based catalysts.[5] Small organic molecules, including carbenes, thioureas, and guanidines (TBD) were thus shown to drive various polymerizations, enabling good selectivities, relatively high rates[6] and excellent functional group tolerance. Polyurethane synthesis is well-known to be catalyzed by tertiary amines, such as 1,4-diazabicyclo[2.2.2]octane (DABCO), 2,2′-bis-(dimethylaminoethyl ether) (BDMAEE) or amidines such as 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU).[7] However, none of these organocatalysts have permitted yet reaching the reaction rates attained with tin reagents. The search for more efficient catalysts that would also display delayed catalytic activity allowing the premixing of the monomers is thus continuing and has concentrated a lot of efforts recently.[8] In the course of our investigations on the synthesis of biosourced polyurethanes,[9] we studied the catalytic activities of several nitrogen-based organocatalysts. Among the various small organic activators that were tested, cyclic guanidines were shown to exhibit attractive catalytic activities, rivaling with the commonly used dibutyltin dilaurate (DBTDL). We provide here a preliminary account of these studies, including the selection of the best catalysts using polymerization in bulk and a comparison with closely related amidines DBU and DBN.

RESULTS AND DISCUSSION

Screening of Organocatalysts in Polyurethane Synthesis Using IPDI and PEG-600 (or PTMO-650) as Precursors. The synthesis of PU from equimolar amounts of commercially available isophorone diisocyanate (IPDI) and dried poly(ethylene glycol) 600 (PEG-600) (Scheme 1) was first studied using a panel of structurally and functionally different basic/nucleophic organocatalysts **2**−**8** (1 mol %) (Scheme 2). DABCO and DBU, standard catalysts for PU synthesis, were thus studied, as well as amino-pyridine and guanidines, including acyclic guanidines **7a**,**b** and guanidine dimer **8** (obtained by coupling TBD **2a** with 1,4-bis-

Received: December 6, 2011
Revised: January 22, 2012
Published: February 21, 2012

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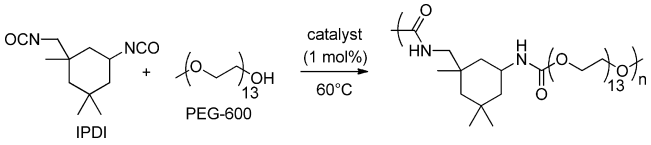
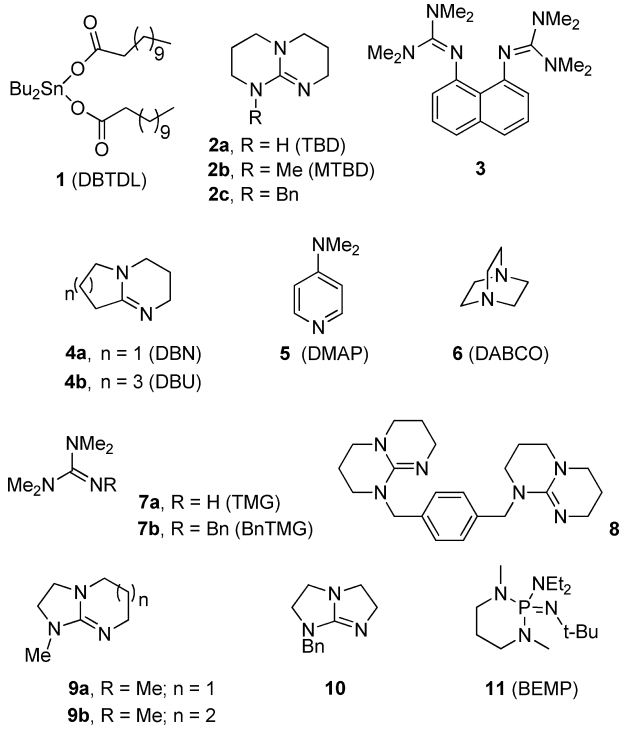
Scheme 1. Organocatalyzed Synthesis of Polyurethane (PU) from IPDI and PEG-600



Scheme 2. Structure of Organocatalysts 2−11



(bromomethyl)benzene) (Supporting Information). Dibutyltin dilaurate **1** was used as a reference. IPDI and PEG-600 were investigated as to perform the reaction in bulk at 60 °C, the low viscosity of the polymer formed allowing aliquots sampling and monitoring of the reaction using FT-IR. Reaction progress was estimated by measuring the disappearance of the NCO and OH stretching vibrations at 2252 and 3464 cm^{-1}, respectively, and the formation of the intense urethane C═O bond at 1715 cm^{-1} as a function of time. Quantification was carried out, relying on the unchanged absorption of CH_2 bonds at 2867 cm^{-1}. From these preliminary experiments, summarized in Figure 1, most catalysts were found to be active in the polyaddition of PEG-600 with IPDI, leading to PUs with complete conversion after 1 h, all catalysts leading to 50% conversion after less than 45 min. Amidines and guanidines clearly emerged as superior catalysts. Strikingly, strongly basic and nucleophilic guanidine MTBD **2b** and amidine DBU **4b** were both found to be more active than DBTDL, leading to complete conversion after only 15 min. They exhibit remarkable catalytic activities as compared to other less basic, hence nucleophilic heterocycles including substituted DMAP **5** and DABCO **6**, which required almost 5 h to reach completion. In contrast, guanidine **2a** (TBD) which was recently reported to be an excellent catalyst for polyester synthesis, acting through an original dual activation,[10] and for polyurethane synthesis[11] displayed poor activity as compared to *N*-alkylated guanidine **2b**. This behavior contrasts with the observations of Waymouth and Hedrick during catalyzed ring-opening polymerization of lactides and lactones, where **2a** was reported to be more efficient than **2b**.[12] Acylic guanidines **7a**,**b** were slightly less reactive.[13] It is worth noticing that the presence of a free imino group in **7a** had no effect on the rate of the reaction (*vide infra*). Finally, the dimer **8** showed the same reactivity than MTBD when used in only 0.5 mol %. PU characteristics, with respect to molecular weight and molecular weight distribution obtained from SEC analysis are given in Table 1. These data of PU samples quenched with methanol after 18 h clearly demonstrate the efficiency of the organocatalysts in comparison to DBTDL **1** (entries 2−3). In all cases, PUs with reasonable high molecular weights could be obtained, in particular when mechanical stirring was used to overcome the viscosity increase (entries 3, 6, 7, 9). PUs were carefully analyzed through FT-IR spectroscopy (see Supporting Information). Whatever the catalyst used, all PUs exhibit similar molecular IR spectra without detectable isocyanurate, allophanate or urea bands that prove the high selectivity of the tested organocatalysts. It is finally worth adding that treatment of polyurethanes with **2b** in the presence of EtOH was tested and led to no noticeable changes in the ^1H NMR spectrum, demonstrating that guanidine **2b** does not catalyze the transurethanization reaction.

The scope of applications of the catalyzed PU synthesis was then further extended to the polymerization of IPDI and poly(tetramethylene oxide) (PTMO-650) restricting our study to the most efficient amidine and guanidine catalysts (1 mol %) (Scheme 3). As above, equimolar amounts of IPDI and PTMO-650 were reacted in bulk at 60 °C in the presence of various organocatalysts. Time course of the reaction, summarized in Figure 2, confirm the general trend observed in the previous polymerization experiment. While the activity of the tin catalyst **1** does not seem to be affected by traces of water present in commercial PTMO-650 (entry 1, Table 2), such was not the case with guanidines. Overlapping FT-IR spectra of PU prepared using tin catalyst **1** and MTBD **2b** showed no significant difference, except a small enlargement of the band at 1716 cm^{-1} due to the presence of traces of urea (see Supporting Information). This could be considerably reduced through purification by azeotropic distillation (toluene) of PTMO-650 before use. As indicated by experiments in entry 4 (vs entry 3), PU of higher molecular weights were repeatedly obtained upon catalysis with **2b**, when water was removed from the diol prior to the reaction. Use of a slight excess of IPDI also provided higher molecular weight (entry 5), proving that some NCO function is generally lost through secondary reactions, in particular reaction with water traces (leading to urea). MTBD **2b** was found to be as active as DBTDL, leading to a complete conversion after 1 h. Interestingly, **2b** and its dimeric analogue **8** displayed much higher reactivity than the unsubstituted TBD **2a** (entry 3 and 10 vs 2), in contrast with precedent in the literature.[10,11] The analogous DBN **4a** (entry 8) showed a surprising behavior with a very fast initial polymerization rate, leading to more than 50% of the conversion of NCO functions after 1 min and then a complete loss of activity, suggesting that inhibition of the catalyst occurs very rapidly (*vide infra*). The superbasic "proton sponge" but poorly nucleophilic naphthylbisguanidine (TMGN) **3**,[14] surprisingly led to a poor catalytic activity. Considering the high efficiency of the cyclic penta-alkyl guanidine catalysts **2a**−**c** in the PU synthesis, new bicyclic guanidines, having different ring sizes, were prepared[12b,15] (Supporting Information) and tested in the con-

dx.doi.org/10.1021/ma2026258 | *Macromolecules* 2012, 45, 2249−2256

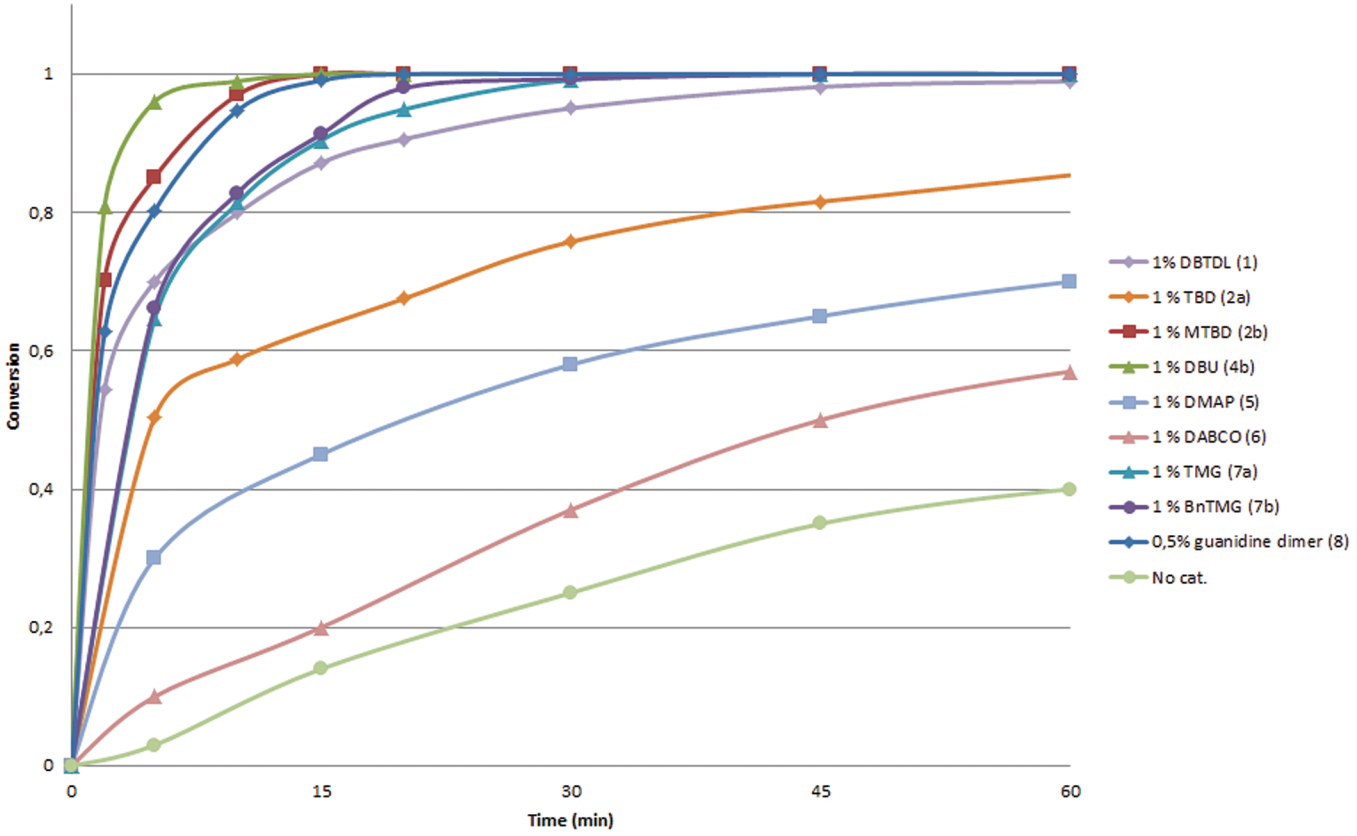


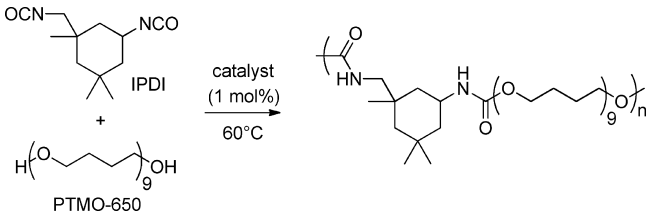
Figure 1. Screening of various organocatalysts in the synthesis of PU from IPDI and PEG-600.

Table 1. Synthesis of Polyurethanes from Bulk Polyaddition of IPDI and PEG-600 (Stoichiometric Ratio) in the Presence of Organocatalysts 2−8 at 60°C

entry	catalyst[a]	M_w (g mol^{-1})[b,c]	M_n (g mol^{-1})[b,c]	$D = M_w/M_n$[c]
1	no catalyst	35 000	25 000	1.40
2	DBTDL **1**	48 100	33 400	1.44
3[d]	DBTDL **1**	54 000	34 600	1.56
4	**2a**	28 900	21 700	1.33
5	**2b**	33 700	24 800	1.36
6[d]	**2b**	48 000	33 100	1.45
7[d]	**4b**	74 000	39 800	1.89
8	**7a**	29 800	22 400	1.33
9[d]	**7a**	43 000	30 100	1.43
10	**7b**	29 300	22 000	1.33
11	**8**[e]	31 250	23 300	1.34

[a]1 mol % of catalyst was used. [b]Aliquots of PU were taken after quenching the reaction mixture with MeOH (after 18 h of stirring). [c]Estimated through SEC analysis onto PU samples quenched as above; DMF as eluent with PS standards. [d]Performed using a mechanical stirrer. [e]0.5 mol % of dimeric catalyst **8** was used.

Scheme 3. Organocatalyzed Synthesis of Polyurethane (PU) from IPDI and PTMO-650



densation between IPDI and PTMO-650. The size of the ring of the different guanidines was found to have an effect on the polymerization rate. Guanidine **10** thus led to a lower activity than the larger analogues **9a** and **9b** (entry 11−13), with incomplete conversion of NCO moieties even after 3 h, indicating that an amidyl functional group (N−CH═N) embedded in a 6- or 7-membered ring is required to get efficient catalysis. As above, dimeric **8** at 0.5 mol % showed the same reactivity than **2b**. Highly basic phosphazene **11**[15] led to reasonable catalytic activity, albeit lower than that observed with guanidines (entry 14). Finally, the reaction afforded the PU with complete conversion after 6 h at 60 °C using only 0.05 mol % of MTBD **2b**, demonstrating the high efficiency of such guanidines (entry 15). As already discussed with PEG-600 as diol monomer, Table 2 below indicates that polymerization in the presence of guanidines provide PUs having satisfying molecular weights. These studies demonstrate unambiguously that substituted guanidines exhibit unprecedented catalytic activities in polymerization of diols and di-isocyanates, whatever the nature of the monomer with catalyst loading as low as 0.05 mol %.

Preliminary Mechanistical Investigations. Two mechanisms have been proposed to rationalize the course of the base/nucleophile-catalyzed addition of alcohols onto isocyanates, which are still subject to controversy. The first kinetic studies by Baker et al.[16] suggested that a nucleophilic catalysis was involved, with the addition of the catalyst onto the N═C═O functional group as a preliminary step (nucleophilic catalysis mechanism). More recent studies[17] showed that this mechanism is not general and that activation of the alcohol by the basic catalyst (general base catalysis mechanism) more appropriately describes the addition of an alcohol onto an

dx.doi.org/10.1021/ma2026258 | *Macromolecules* 2012, 45, 2249−2256

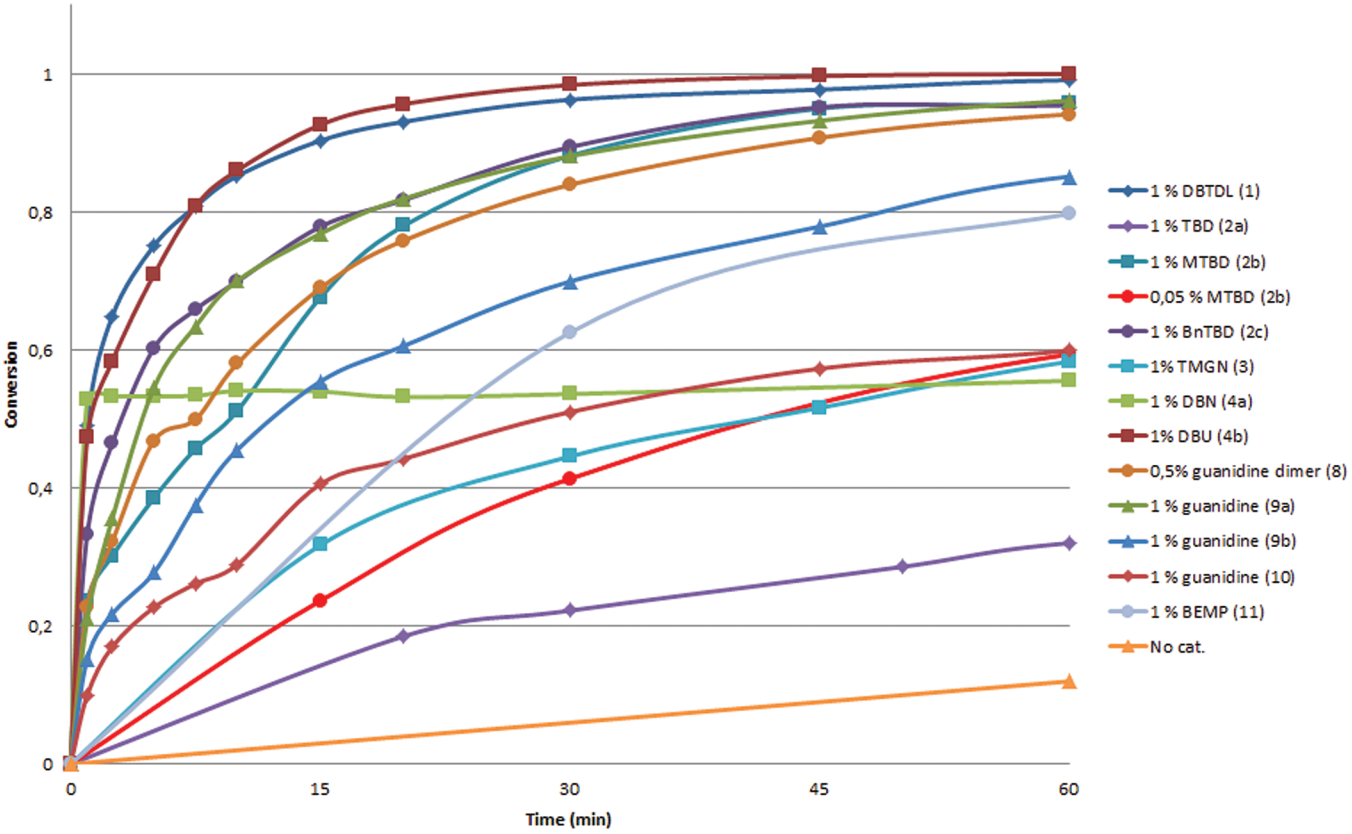


Figure 2. Screening of various organocatalysts in the synthesis of PU from IPDI and PTMO-650.

Table 2. Polyaddition of IPDI and PTMO-650 using organocatalysts 2a–c, 4a,b, 8–10

entry	catalyst[a]	convn (%)[b]	M_w (g mol^{-1})[c,d]	M_n (g mol^{-1})[c,d]	$D = M_w/M_n$[d]
1[e]	DBTDL **1**	>98	93 000	67 900	1.37
2[e]	**2a**	82	21 000	14 200	1.48
3[e]	**2b**	>98	36 000	26 700	1.35
4[f]	**2b**	>98	50 200	32 600	1.54
5[g]	**2b**	>98	85 000	58 600	1.45
6[e]	**2c**	>98	42 700	29 400	1.45
7[e]	**3**	>98	28 250	18 800	1.50
8[e]	**4a**	86	-	-	-
9[e]	**4b**	>98	31 500	20 700	1.52
10[e]	**8**[h]	>98	32 300	21 500	1.50
11[e]	**9a**	>98	41 600	27 500	1.51
12[e]	**9b**	>98	50 400	32 500	1.55
13[e]	**10**	>98	33 800	21 900	1.54
14[e]	**11**	>98	29 600	19 500	1.52
15[e]	**2b**[i]	>98	55 000	34 800	1.58

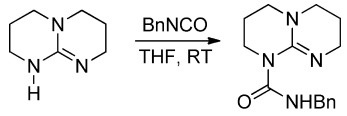
[a]1 mol % of catalyst was used. [b]Estimated by measuring, using FT-IR, the disappearance of the isocyanate N=C = O band. [c]Aliquots of PU were taken after quenching the reaction mixture with MeOH (after 18 h of stirring). [d]Estimated through SEC analysis; DMF as eluent with PS standards. [e]The PTMO-650 used was not dried before polymerization. [f]The PTMO-650 used was carefully dried through azeotropic distillation in toluene before polymerization. [g]1.1 equiv of IPDI was used for 1 equiv of commercial PTMO-650. [h]0.5 mol % of **8** was used. [i]0.05 mol % of **2b** was used.

isocyanate.[18] Several refinements on the latter mechanism (complete proton transfer or concerted single step proton transfer followed by nucleophilic attack) have also been proposed. Finally, dual activation of the alcohol and the isocyanate may also be invoked. Recent reports on this latter mode of action have been reported, for instance in ROP of lactides.[10,19] In order to get better insights into the mechanism of the guanidine-catalyzed addition of alcohols onto isocyanates, a series of experiments with guanidine **2a–b** was thus performed using 2,3-dimethoxyphenethyl alcohol and benzyl isocyanate (BnNCO) as model compounds in solution (Supporting Information). For instance, ^{1}H NMR of an equimolar mixture of this alcohol model and **2b** revealed proton chemical shifts for the alcohol hydrogen, which indicates that hydrogen bonded complex MTBD-2,3-dimethoxyphenethyl alcohol might be involved at some stage (Supporting Information).[10,20] However, activation through general base catalysis should also imply that the reaction rate increases with the basicity of the catalyst.[21] As shown above, catalytic activities of organocatalysts follow the order: DABCO **6** < DMAP **5** (17.95) < TBD **2a** (26.03) < TMGN **3** (25.4) < BEMP **11** (27,5) < TMG **7a** (23.3) ~ BnTMG **7b** < MTBD **2b** (25.43) ~ DBU **4b** (24.33), which does not fit with the corresponding pK_a's (in CH_3CN).[21,22] It is thus worthy of note that bis-guanidine **3** (TMGN) and phosphazene **11** led to poor activity despite their strong basicity (Figure 2). The difference in catalytic activity between TMGN **3** and MTBD **2b**, which exhibit similar pK_a's (25.4 and 25.43 respectively) during polymerization of IPDI and PTMO-650 (Figure 2), is also striking, suggesting that other mechanism(s) than general base catalysis may operate.[10] Additional experiments led us speculate that a nucleophilic mechanism should not be completely ruled out (*vide infra*). For instance, the low nucleophilicity of **3**, due to steric hindrance around the nitrogen centers would explain its low catalytic activity, supporting such a mechanism. Figures

dx.doi.org/10.1021/ma2026258 | *Macromolecules* 2012, 45, 2249–2256

1 and 2 also show that TBD **2a**, which is more basic than MTBD **2b** and TMG **7a**, is comparatively a weaker catalyst. This was ascribed to the ability of **2a** to react with isocyanates. We thus observed that reaction of a 1:1 mixture of **2a** and BnNCO, led to the rapid formation of the corresponding urea **12** (Scheme 4).[23] Interestingly, the latter was shown to catalyze

Scheme 4. Reaction of TBD 2a with Benzylisocyanate

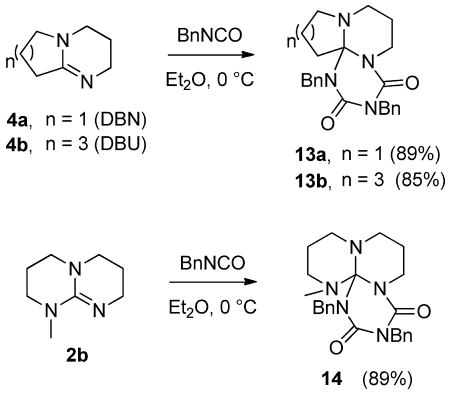


2a **12** (89%)

the formation of polyurethanes from IPDI and PTMO-650 at 60 °C (Figure 3), with the same efficiency than TBD **2a** alone, suggesting that the formation of PU is probably catalyzed by an urea such as **12** and not by **2a**.[11,13] This also indicates that guanidines are likely to react with isocyanates in the presence of alcohols in the medium (*vide infra*). The reduced catalytic activity of **2a** as compared to the alkylated analogue **2b**, would be due to the presence of the electron-withdrawing C(=O)NHR moiety, as in **12**, which likely decreases the electron density on the guanidine framework, reducing both the basicity and the nucleophilicity of **2a**. The high reactivity of TBD toward electrophiles (including CO_2)[24] also implies that impurities in the medium might reduce its catalytic activity. Repeating the polymerization using freshly sublimated TBD **2a** however led to similar results than those obtained with unpurified commercial TBD (Figure 3).

Finally, reasoning that amidines **4a,b** might catalyze the above reaction through a mechanism similar to that of guanidines, the reactivity of **4a,b** toward isocyanates was studied, treating both amidines with BnNCO. Pleasingly, this led to the formation, in good yields, of tricyclic compounds **13a,b** incorporating two molecules of BnNCO (Scheme 5).[25] Similarly, guanidine **2b** provided under the same conditions, compound **14** in high yield.[26] Interestingly, when **13a**, **13b**, and **14** were left in THF under reflux in the presence of a primary

Scheme 5. Reactions of 2b and 4a,b with BnNCO



4a, n = 1 (DBN)
4b, n = 3 (DBU)

13a, n = 1 (89%)
13b, n = 3 (85%)

2b

14 (89%)

alcohol such as 3,4-dimethoxyphenethyl alcohol used previously, they exhibited contrasting behavior. While **13a** and **13b** were stable under these conditions, **14** returned guanidine **2b** along with the corresponding carbamate (Supporting Information). The rapid deactivation of **4a** during reaction of IPDI and PTMO-650 (Figure 2) might thus be explained by the irreversible formation in the medium of an adduct between **4a** and IPDI, similar to **13a**. The difference in reactivity between DBN **4a** and DBU **4b** (Figure 2) is striking and may be rationalized invoking a much higher reactivity of **4a** toward isocyanates as compared to **4b**. Although calorimetric experiments have not been performed, we noticed that addition of BnNCO onto **4a** was much more exothermic than that with **4b**. As the formation of **13a** is not reversible, no free amidine **4a** remains in the medium during polymerization, thus explaining its *in situ* deactivation after less than 1 min. This also shows that the free amidine is the real catalyst in this case, in contrast to TBD **2a** where the urea adduct, **12**, catalyzes the reaction. This difference in reactivity between closely related bicyclic amidines points out again the importance of the ring size in these bicyclic organocatalysts. The difference in stability between adducts **12** and **14** issued from guanidines and **13a,b** generated from amidines is also of interest and suggests that cyclic *N*-alkylguanidines such as **2b** should be superior and selective

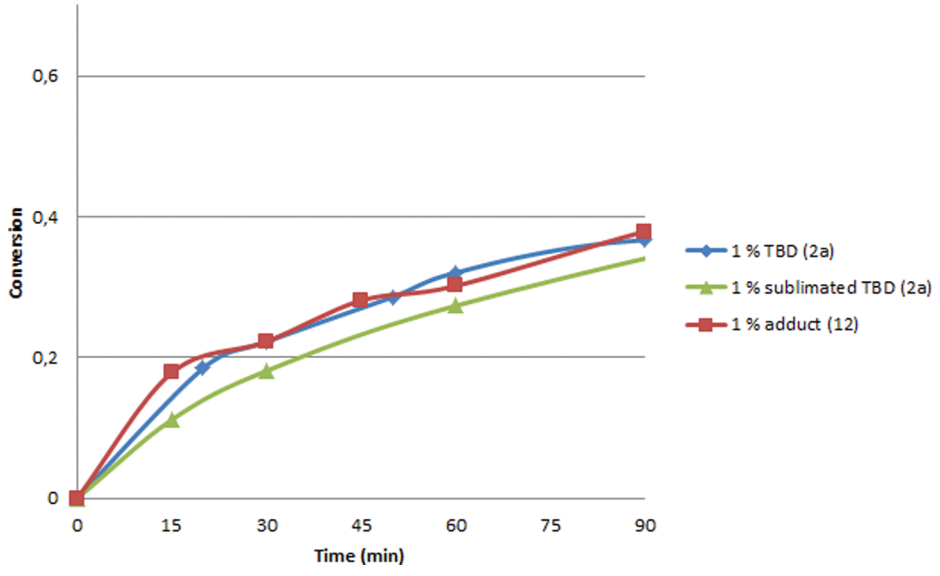


Figure 3. Organocatalyzed polymerization of IPDI and PTMO-650 in the presence of **2a** and urea **12**.

dx.doi.org/10.1021/ma2026258 | *Macromolecules* 2012, 45, 2249–2256

catalysts, whatever the reactivity of isocyanates, as their adducts form reversibly, thus allowing the catalysis, which is not the case with amidine adducts such as **13a,b**.

In order to obtain further mechanistical insights, we finally varied the order of addition of the reagents and catalysts (**2b**) and compare these new conditions (conditions B and C, Figure 4) with those used previously (conditions A, Figure 1 and 2).

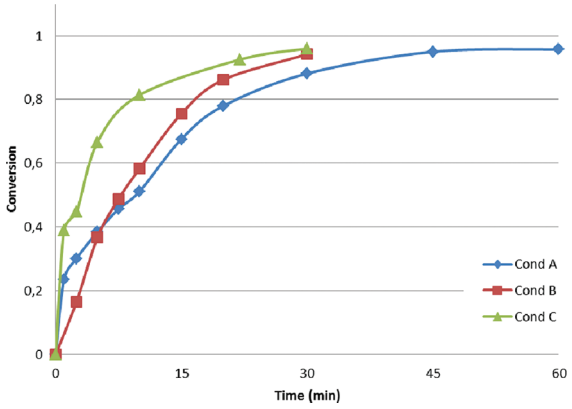


Figure 4. Organocatalyzed polymerization of IPDI and PTMO-650 varying the order of addition. Condition A: IPDI and PTMO-650 are premixed at 20 °C, then MTBD **2b** is added, and the reaction mixture is heated to 60 °C. Condition B: catalyst **2b** is premixed with IPDI at 20 °C before the addition of PTMO-650. The reaction mixture is then heated to 60 °C. Condition C: catalyst **2b** is premixed with PTMO-650 at 20 °C before the addition of IPDI. The reaction mixture is then heated to 60 °C.

For instance, when guanidine **2b** was premixed with IPDI before the addition of the alcohol (condition B), one observes a rather slow initiation period, that may be attributed to the *in situ* formation of an adduct such as **14**, which decomposition would be necessary to restore the catalytic activity. In turn, when **2b** was premixed with the alcohol (PTMO, conditions C), the reaction was found to be slightly faster as compared to conditions A and also led to PU with higher molecular weight (Table 3). This may be explained by an H-bonding activation

Table 3. Organocatalyzed Polymerization of IPDI and PTMO-650 Varying the Order of Addition

conditions	convn (%)[a]	M_w (g mol^{-1})[b,c]	M_n (g mol^{-1})[b,c]	$D = M_w/M_n$[c]
conditions A	>98	36 000	26 700	1.35
conditions B	>98	28 700	18 400	1.56
conditions C	>98	61 300	38 800	1.58

[a]Estimated by measuring, using FT-IR, the disappearance of the isocyanate N=C=O band. [b]Aliquots of PU were taken after quenching the reaction mixture with MeOH (after 18 h of stirring). [c]Estimated through SEC analysis; DMF as eluent with PS standards.

of the alcohol by the guanidine (similar to the MTBD-3,4-phenethyl alcohol complex above), that would accelerate the addition of the alcohol onto the isocyanate, and in the same time, prevent the formation of an adduct such as **14** mentioned above.

In summary, we have shown that addition of diols onto diisocyanates is efficiently catalyzed by guanidines, leading to polyurethanes with high molecular weight. Cyclic guanidines are slightly more reactive than acyclic ones as in the former, the ring constrains the nitrogen into a conformation where the lone pairs are properly aligned to favor lone pairs delocalization.[27] Preliminary mechanistical investigations provide some original and unexpected features of this catalysis with the isolation of adducts issued from the nucleophilic addition of guanidines onto isocyanates. Similar behavior was observed with amidines. Although the presence of these adducts in the medium in the presence of the alcohol partner has not been firmly proved (*vide supra*), these investigations suggest that the nucleophilic catalysis mechanism should not be *a priori* ruled out with these strongly basic catalysts. This would involve an initial nucleophilic attack of the guanidine onto the isocyanate C=O functional group[28,29] (nucleophilic monomer activation), followed by the reaction of the activated zwitterionic acyl intermediate with the alcohol partner to provide the urethane linkage (Figure 5). Activation of the alcohol by a general base

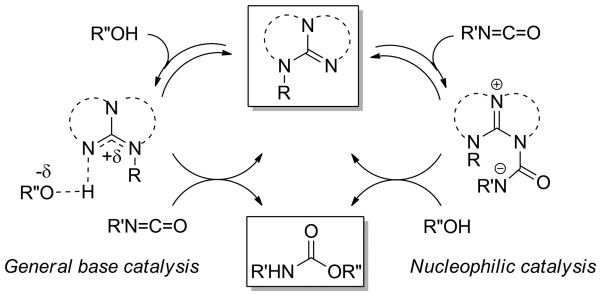


Figure 5. Catalytic cycles for the formation of the urethane linkage using guanidines as organocatalysts.

catalysis mechanism may also operate as suggested by ^{1}H NMR studies on model alcohols. It is also worth adding that the order of addition of the different partners might also influence the mechanistical outcome of the process as shown by experiments summarized in Figure 4 and Table 3. Further kinetic investigations along with theoretical studies at the DFT level will thus be needed to definitely establish the mechanism of these guanidine-catalyzed PU synthesis. Studies along these lines are now underway in our laboratory.

CONCLUSION

We have reported along these lines the efficiency of cyclic guanidines as catalysts in the polyaddition of diols onto diisocyanates. Relatively high molecular weight polyurethanes with a good control of the molecular structure are obtained without the formation of allophanates or isocyanurates moieties. A straightforward preparation of guanidines has been devised enabling an easy access to a wide range of new guanidine structures. Elaboration of new guanidines based on readily available TBD **2a** and synthesis of 5-membered ring guanidines such as **9** and **10** offers an alternative route to further extend the screening. Efforts are now focusing on kinetic studies to get insights into the mechanism of this catalyzed PU synthesis and on the design of novel and more efficient catalysts.

EXPERIMENTAL SECTION

General Information. All reactions were carried out under an argon atmosphere with dry solvents under anhydrous conditions, unless otherwise noted. Yields refer to chromatographically and spectroscopically (^{1}H and ^{13}C NMR) homogeneous materials, unless otherwise stated. Commercial reagents were used without further purification, unless otherwise stated. ^{1}H NMR and ^{13}C NMR were recorded on a Brüker AC-300 FT and (^{1}H: 300 MHz, ^{13}C: 75.46

dx.doi.org/10.1021/ma2026258 | Macromolecules 2012, 45, 2249–2256

MHz) and a Brüker ARX-400 FT (^{1}H: 400 MHz, ^{13}C: 100.6 MHz) using $CDCl_3$ as internal reference unless otherwise indicated. The chemical shifts (δ) and coupling constants (J) are expressed in ppm and Hz, respectively. The following abbreviations were used to explain the multiplicities: s = singlet, d = doublet, t = triplet, q = quartet, quint = quintet, m = multiplet, br = broad. IR spectra were recorded on a Perkin-Elmer 1710 spectrophotometer, on a Perkin-Elmer Paragon 500 FT-IR spectrophotometer or on a Perkin-Elmer Mattson Unicam 500 16PC FT-IR using a ZnSe crystal ATR accessory. High resolution mass spectra (HRMS) were recorded with a Q-TOF 2 spectrometer in the electrospray ionization (ESI) mode. Melting points were not corrected and determined by using a Büchi Totolli apparatus. Merk silica gel 60 (70−230 mesh) was used for flash chromatography. Size exclusion chromatography (SEC) analyses were performed at room temperature in DMF at 80 °C with a setup consisting of a PL-GPC 50 plus Integrated GPC from Polymer laboratories-Varian and a series of three columns PLgel 5 μm MIXED-D. The elution of the filtered samples was monitored using simultaneous UV and refractive index detections. The elution times were converted to molar mass using a calibration curve based on low dispersity (M_w/M_n) polystyrene (PS) standards.

General Procedure for the Synthesis of Polyurethanes. IPDI (0.8 mL, 3.78 mmol) was added to PTMO-650 (2.45 g, 3.78 mmol) at room temperature. A solution of catalyst (75.5 μmol, 0.02 mmol) in THF (0.5 mL) was then added and the mixture stirred at 60 °C. Aliquots were taken at various period of time and FT-IR spectra recorded to monitor the time course of the reaction (see Figure 2 and Supporting Information). After 18 h, the reaction mixture was quenched with methanol and the polymer analyzed using SEC (Table 2).

Synthesis of Urea 12. Benzylisocyanate (200 μL, 1.63 mmol) was added dropwise to a solution of TBD **2a** (227 mg, 1.63 mmol) in THF (6 mL) leading to an exothermic reaction. The homogeneous reaction mixture was stirred 1 h at room temperature (*ca.* 17 °C). The solvent was then removed under vacuum affording a viscous oil. A small amount of ether was then added to precipitate traces of unreacted **2a**. The solid was removed by filtration and the filtrate was concentrated under vacuum to afford the expected product **12** as a pale yellow oil (397 mg, 89%). IR (neat): υ = 2932, 2852, 1664, 1543, 698 cm^{-1}. ^{1}H NMR (C_6D_6, 300 MHz): δ = 12.2 (br s, 1H), 7.44−7.37 (m, 2H), 7.19−7.09 (m, 2H), 7.07−6.99 (m, 1H),4.68 (d, J = 5.6 Hz, 2H), 3.83−3.75 (m, 2H), 3.19 (t, J = 5.7 Hz, 2H), 2.42 (t, J = 6.2 Hz, 2H), 2.23 (t, J = 6.5 Hz, 2H), 1.29 (qt, J = 6.4 Hz, 2H), 1.25−1.15 ppm (m, 2H). ^{13}C NMR (C_6D_6, 75 MHz): δ = 157.0, 149.8, 141.2, 127.9, 126.8, 49.0, 48.4, 44.7, 43.2, 40.1, 22.8, 22.2 ppm. HRMS (ESI): m/z calcd for $C_{15}H_{21}N_4O$ $[M + H]^+$, 273.1715; found, 273.1712.

General Procedure for the Synthesis of Adducts 13a,b, 14. Benzylisocyanate (1.9 mmol) was added dropwise to a solution of amidine (or guanidine) (1 mmol) in Et_2O (1 mL) at 0 °C. The homogeneous reaction mixture was then stirred 5 min at 0 °C. After recrystallization of the crude mixture at −40 °C, the crystals were filtered and washed with a small amount of ether affording the expected compound as colorless solid.

MTBD-2 BnNCO Adduct (14). Mp = 96−97 °C (THF/pentane). IR (neat): υ = 2925, 1683, 1645, 1470, 1377, 751, 700 cm^{-1}. ^{1}H NMR (C_6D_6, 300 MHz): δ = 7.79−7.73 (m, 2H), 7.56−7.50 (m, 2H), 7.25−7.01 (m, 6H), 5.31 (dd, J = 11.7 Hz, J = 13.7 Hz, 2H), 5.06 (d, J = 14.1 Hz, 1H), 4.63−4.52 (m, 1H), 4.35 (d, J = 14.1 Hz, 1H), 2.55−2.42 (m, 2H), 2.30−2.08 (m, 4H), 1.79 (s, 3H), 1.72−1.47 (m, 2H), 1.25−1.08 ppm (m, 3H). ^{13}C NMR (C_6D_6, 75 MHz): δ = 153.7, 151.4, 140.5, 139.1, 130.0, 129.4, 128.5, 127.5, 126.9, 97.3, 47.8, 46.8, 45.7, 45.1, 42.2, 36.4, 35.7, 23.3, 20.5 ppm. HRMS (ESI): m/z calcd for $C_{24}H_{30}N_5O_2$ $[M + H]^+$, 420.23995; found, 420.2396.

■ ASSOCIATED CONTENT

Supporting Information

General experimental procedures and information, synthesis and spectroscopic data for guanidines **9a,b**, **10**, time course experiments, and the corresponding FT-IR and ^{1}H NMR data. This material is available free of charge via the Internet at http://pubs.acs.org

■ AUTHOR INFORMATION

Corresponding Author

*(H.C.) E-mail: cramail@enscbp.fr. Fax: (+ 33) 05 40 00 84 87. (Y.L.) E-mail: y.landais@ism.u-bordeaux1.fr. Fax: (+ 33) 05 40 00 62 86.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

We thank the French "Agence Nationale de la Recherche" (ANR-09-CP2D-15), and the French Ministry of Research and Technology for financial support.

■ REFERENCES

(1) (a) Oertel, G. *Polyurethane Handbook*; Hanser Publishers: Munich, Germany, 1985. (b) Wirpska, Z. *Poly(urethane)s: Chemistry, Technology, and Application*: Ellis Horwood: London, 1993. (c) Becker, R. L. Thiele, *Isocyanate reactions in Polyurethane catalysis*: CRC Press, Inc.: Boca Raton, FL, 1996; p 6940. (d) Hepburn, C. *Polyurethane Elastomers*; Springer: Berlin, 1992.

(2) (a) Bayer, O. *Angew. Chem.* **1947**, *59*, 257−272. (b) Bayer, O.; Müller, E. *Angew. Chem.* **1960**, *72*, 934−939.

(3) (a) Lipatova, T. E.; Bakalo, L. A.; Niselsky, Yu N.; Sirotinskaya, A. L. *J. Macromol. Sci.—Chem.* **1970**, *A4* (8), 1743−1758. (b) Frisch, K. C.; Rumao, L. P. *J. Macromol. Sci.—Rev. Macromol. Chem.* **1970**, *5c*, 103−149. (c) Luo, S. G.; Tan, H. M.; Zhang, J. G.; Wu, Y. J.; Pei, F. K.; Meng, X. H. *J. Appl. Polymer Sci.* **1997**, *65*, 1217−1225. (d) Majundar, K. K.; Kundu, A.; Das, I.; Roy, S. *Appl. Organomet. Chem.* **2000**, *14*, 79−85.

(4) For an overview see: (a) Toxicological Profile for Tin and Tin compounds, ATSDR (Agency for Toxic Substances and Disease Registry) , 2005. (b) Revised assessment of the risks to health and the environment associated with the use of the four organotin compounds TBT, DBT, DOT and TPT, The Scientific Committee on Health and Environmental Risks (SCHER), 2006.

(5) (a) Kamber, N. E.; Jeong, W.; Waymouth, R. M.; Pratt, R. C.; Lohmeijer, B. G. G.; Hedrick, J. L. *Chem. Rev.* **2007**, *107*, 5813−5840. (b) Raynaud, J.; Ciolino, A.; Baceiredo, A.; Destarac, M.; Bonnette, F.; Kato, T.; Gnanou, Y.; Taton, D. *Angew. Chem., Int. Ed.* **2008**, *47*, 5390−5393. (d) Raynaud, J.; Gnanou, Y.; Taton, D. *Macromolecules* **2009**, *42*, 5996−6005.

(6) For the observations of similar reaction rates between organo- and metal-based catalysts, see: McLaughlin, M.; Garcia Rubio, S.; Muthyala, R.; Antunes, O. A. C.; Tilstam, U.; Zlota, A.; Yadav, G. D.; Laird, T. *Org. Process Res. Dev.* **2006**, *10*, 853−865.

(7) Silva, A. L.; Bordado, J. C. *Catal. Rev.* **2004**, *46*, 31−51.

(8) (a) Bantu, B.; Manohar Pawar, G.; Decker, U.; Wurst, K.; Schmidt, A. M.; Buchmeiser, M. R. *Chem.—Eur. J.* **2009**, *15*, 3103−3109. (b) Bantu, B.; Manohar Pawar, G.; Wurst, K.; Decker, U.; Schmidt, A. M.; Buchmeiser, M. R. *Eur. J. Inorg. Chem.* **2009**, *15*, 1970−1976.

(9) (a) Cramail, H.; Boyer, A.; Cloutet, E.; Bakhiyi, R.; Alfos, C. WO 2011030076, FR2950051. (b) Cramail, H.; Boyer, A.; Cloutet, E.; Alfos, C. WO 2011030075, FR2950052. (c) Cramail, H.; Boyer, A.; Cloutet, E.; Alfos, C. WO 2011045536, FR2951166. (d) Palaskar, D. V.; Boyer, A.; Cloutet, E.; Alfos, C.; Cramail, H. *Biomacromolecules* **2010**, *11*, 1202−1211. (e) Boyer, A.; Cloutet, E.; Tassaing, T.; Gadenne, B.; Alfos, C.; Cramail, H. *Green Chem.* **2010**, *12*, 2205−2213. (f) Palaskar, D. V.; Boyer, A.; Cloutet, E.; Le Meins, J. F.; Gadenne, B.; Alfos, C.; Farcet, C.; Cramail, H. *J. Polym. Sci., Part A: Polym. Chem.* **2012**, DOI: 10.1002.

(10) (a) Lohmeijer, B. G. G.; Pratt, R. C.; Leibfarth, F.; Logan, J. W.; Long, D. A.; Dove, A. P.; Nederberg, F.; Choi, J.; Wade, C.; Waymouth, R. M.; Hedrick, J. L. *Macromolecules* **2006**, *39*, 8574−

8583. (b) Chuma, A.; Horn, H. W.; Swope, W. C.; Pratt, R. C.; Zhang, L.; Lohmeijer, B. G. G.; Wade, C. G.; Waymouth, R. M.; Hedrick, J. L.; Rice, J. E. *J. Am. Chem. Soc.* **2008**, *130*, 6749−6754.
(11) Tang, D.; Mulder, D.-J.; Noordover, B. A. J.; Koning, C. E. *Macromol. Rapid Commun.* **2011**, *32*, 1379−1385.
(12) (a) Zhang, L.; Pratt, R. C.; Nederberg, F.; Horn, H. W.; Rice, J. E.; Waymouth, R. M.; Wade, C. G.; Hedrick, J. L. *Macromolecules* **2010**, *43*, 1660−1664. (b) Kiesewetter, M. K.; Scholten, M. D.; Kirn, N.; Weber, R. L.; Hedrick, J. L.; Waymouth, R. M. *J. Org. Chem.* **2009**, *74*, 9490−9496.
(13) Maliverney, C.; Saint-Jalmes, L. Patent, WO 2010/043353 A1.
(14) Raab, V.; Kipke, J.; Gschwind, R. M.; Sundermyer, J. *Chem.—Eur. J.* **2002**, *8*, 1682−1693.
(15) Ishikawa, T. *Guanidines in Organic Synthesis in Guanidines, amidines, phosphazenes and related organocatalysts. Superbases for organic synthesis*, Ed. J. Wiley & Sons: Chichester, U.K., 2009 p Chapter 4, pp 93−143.
(16) Baker, J.; Holsworth, J. B. *J. Chem. Soc.* **1947**, 713−726.
(17) Schwetlick, K.; Noak, R.; Stebner, F. *J. Chem. Soc., Perkin Trans. 2* **1994**, 599−608.
(18) Similar mechanisms have been proposed for base-catalyzed alcoholysis of anhydrides, see: Chen, Y.; McDaid, P.; Deng, L. *Chem. Rev.* **2003**, *103*, 2965−2983.
(19) Bonduelle, C.; MartinVaca, B.; Cossio, F. P.; Bourissou, D. *Chem.—Eur. J.* **2008**, *14*, 5304−5312.
(20) Rappo-Abiuso, M.; Llauro, M.-F.; Chevalier, Y.; Le Perchec, P. *Phys. Chem. Chem. Phys.* **2001**, *3*, 99−106.
(21) Bacaloglu, R.; Cotarga, L.; Marcu, N.; Tolgyi, S. *J. Prakt. Chem.* **1988**, *330*, 530−540.
(22) For an exhaustive list of pK_a of amines in CH_3CN, see: Kajjurand, I.; Kütt, A.; Sooväli, L.; Rodima, T.; Mäemets, V.; Leito, I.; Koppel, I. A. *J. Org. Chem.* **2005**, *70*, 1019−1028.
(23) Deutsch, J.; Eckelt, R.; Köckritz, A.; Martin, A. *Tetrahedron* **2009**, *65*, 10365−10369.
(24) Pereira, F. S.; deAzevedo, E. R.; da Silva, E. F.; Bonagamba, T. J.; da Silva Agostini, D. L.; Magalhaes, A.; Job, A. E.; Pérez Gonzalez, E. R. *Tetrahedron* **2008**, *64*, 10097−10106.
(25) Oediger, H., Moeller, F. *Ger. Offen. DE 2640964*, 1978.
(26) Richter, R. *Tetrahedron Lett.* **1968**, *48*, 5037−5039.
(27) Coles, M. P. *Chem. Commun.* **2009**, 3659−3676.
(28) Similar activation of CO_2 by MTBD and TBD has recently been proposed, see: (a) Barbarini, A.; Maggi, R.; Mazzacani, A.; Mori, G.; Sartori, G.; Sartorio, R. *Tetrahedron Lett.* **2003**, *44*, 2931−2934. (b) Villers, C.; Dognon, J.-P.; Pollet, R.; Thuéry, P.; Ephritikhine, M. *Angew. Chem., Int. Ed.* **2010**, *49*, 3465−3468. (c) Das Neves Gomes, C.; Jacquet, O.; Villers, C.; Thuéry, P.; Ephritikhine, M.; Cantat, T. *Angew. Chem., Int. Ed.* **2012**, *51*, 187−190.
(29) Nederberg, F.; Connor, E. F.; Möller, M.; Glauser, T.; Hedrick, J. L. *Angew. Chem., Int. Ed.* **2001**, *40*, 2712−2715.