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Nonpolar Polymers for Metal Sequestration and Ligand and Catalyst Recovery in Thermomorphic Systems

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The recovery and reuse of homogeneous catalysts is of interest for environmental, economic and practical reasons.[1,2] Biphasic systems using ionic liquids,[3,4] fluorous systems,[5] aqueous systems,[6] and thermomorphic polar/nonpolar mixtures[7] all address these issues. Except in the case of fluorous-phase catalysis where lipophilic fluorous-phase soluble lipid ligands are used,[5] catalysts in these systems typically reside in the polar phase of the reaction mixtures at the point of separation. This poses problems if the reaction products or byproducts are polar. Catalysts on cross-linked polymer supports (Merrifield resins) that are always insoluble[8] or on soluble polymers that precipitate from solution[9,10] can be separated from polar solutions, but these systems have the disadvantages of a solid/liquid separation or heterogeneous reaction conditions. Here we describe a liquid/liquid separation process that relies on the ready tunability of polymer solubility to separate and recover ligands, metals, and catalysts in the nonpolar phase of a mixture of polar and nonpolar solvents.

The work described here uses the scheme for biphasic catalyst recovery we call thermomorphic catalysis (Figure 1).[7] In this scheme, a soluble polymer facilitates catalyst recovery and separation of a catalyst from reaction products. The separation in these systems relies on two ideas. The first is that many binary and ternary solvent systems exhibit a reversible increase in miscibility with increasing temperature. The second premise is that a soluble polymer should have a strong phase preference for one phase under biphasic conditions. We demonstrated these ideas with various Rh(I), Pd(0), and Pd(II) homogeneous catalysts attached to the soluble polar poly(*N*-isopropylacrylamide) (PNIPAM) polymer. However, as discussed above, this chemistry is limited in that many reaction products or byproducts are polar and thus not separable from a polar polymer-bound catalyst. For example, reactions such as Heck carbon−carbon bond forming reactions produce salt byproducts that accumulate in the polar, catalyst-containing phase. Here we show that a nonpolar polymer support can be designed to quantitatively stay in the nonpolar phase of a biphasic mixture (an inverse thermomorphic separation) and that such a polymer is useful both in trace metal and catalyst recovery.

Our prior work used polar poly(ethylene oxide) or PNIPAM polymers in aqueous solutions or in the polar phase of a biphasic mixture.[7,10] We here show that changing PNIPAM's *N*-alkyl group to a more lipophilic octadecyl group is enough of a change to invert the polymer solubility so that the polymer would selectively dissolve in the nonpolar phase of a biphasic mixture but stay in solution at elevated temperature. To test this premise and to test the extent to which this polymer would be able to recover a ligand, we prepared poly(*N*-octadecyl-acrylamide-*co*-*N*-acryloxysuccinimide) (PNODAM-*c*-PNASI). The resulting copolymer **1** containing an active ester was then labeled with an azo dye (eq 1) to form PNODAM-**2**. The product *p*-methyl red-labeled polymer was soluble both in heptane and in hot miscible mixtures of heptane and aqueous ethanol or *N*,*N*-dimethylacetamide. More importantly, under resting (25 °C) biphasic conditions with these same solvent mixtures, the dye-labeled polymer was exclusively soluble (>99.9%) in the nonpolar phase.

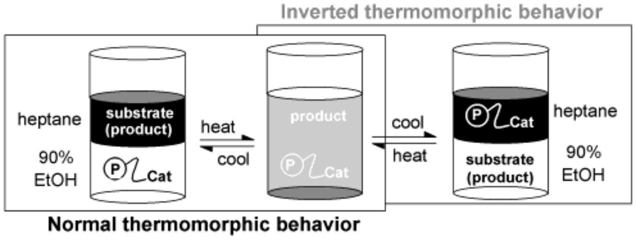
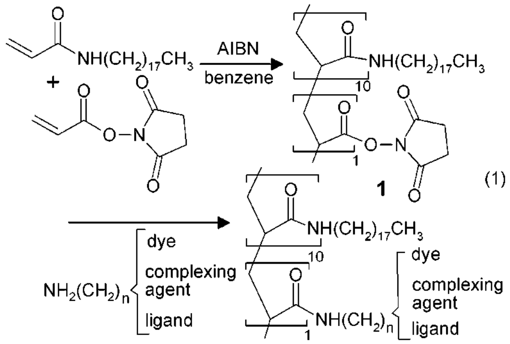


Figure 1. Normal and inverted thermomorphic behavior.



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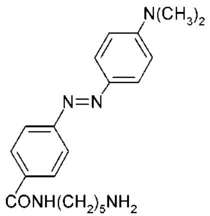

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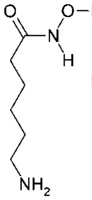

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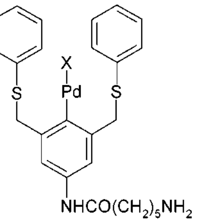

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The PNODAM-polymer **1** was successfully treated with other amines (**3**−**5**) to prepare ligands that can sequester trace metals and catalysts in heptane. Using chemistry like that reported before,[11] we prepared a PNODAM-bound hydroxamic acid (PNODAM-**3**) using **1** and **3**. Heating a biphasic mixture of a heptane solution of this PNODAM-bound hydroxamic acid with an equal volume of an aqueous EtOH solution containing 15.4 ppm of $FeCl_3$ produced a homogeneous red solution at 70 °C. Cooling this solution produced a biphasic mixture with red color only in the heptane phase. Separation of the aqueous EtOH and analysis by DCP (direct current plasma spectroscopy) showed <50 ppb of Fe(III) remained in the aqueous EtOH. A similar

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[1] Baker, R. T.; Tumas, W. *Science* **1999**, *284*, 1477−9.

[2] Sheldon, R. A. *Pure Appl. Chem.* **2000**, *72*, 1233−46.

[3] Wasserscheid, P.; Keim, W. *Angew. Chem., Int. Ed.* **2000**, *39*, 3773. Welton, T. *Chem. Rev.* **1999**, *99*, 2071.

[4] Liu, F.; Abrams, M. B.; Baker, R. T.; Tumas, W. *Chem. Commun.* **2001**, 433−4.

[5] (a) Barthel-Rosa, L P.; Gladysz, J. A. *Coord. Chem. Rev.* **1999**, *190−192*, 587−605. (b) de Wolf, E.; van Koten, G.; Deelman, B.-J. *Chem. Soc. Rev.* **1999**, *28*, 37−41. (c) Horvath, I. T. *Acc. Chem. Res.* **1998**, *31*, 641−50.

[6] (a) Sheldon, R. A. *Pure Appl. Chem.* **2000**, *72*, 1233−1246. (b) Cornils, B. *J. Mol. Catal. A: Chem.* **1999**, *143*, 1−10.

[7] Bergbreiter, D. E.; Osburn, P. L.; Wilson, A.; Sink, E. M. *J. Am. Chem. Soc.* **2000**, *122*, 9058−64.

[8] Sherrington, D. C. *J. Polym. Sci., Part A: Polym. Chem.* **2001**, *39*, 2364−77.

[9] Toy, P. H.; Janda, K. D. *Acc. Chem. Res.* **2000**, *33*, 546−54.

[10] (a) Bergbreiter, D. E. *J. Polym. Sci., Polym. Chem. Ed.* **2001**, *39*, 2352−63. (b) Bergbreiter, D. E. *Catal. Today* **1998**, *42*, 389−97.

[11] Bergbreiter, D. E.; Koshti, N.; Franchina, J. G.; Frels, J. D. *Angew. Chem., Int. Ed.* **2000**, *39*, 1039−42.

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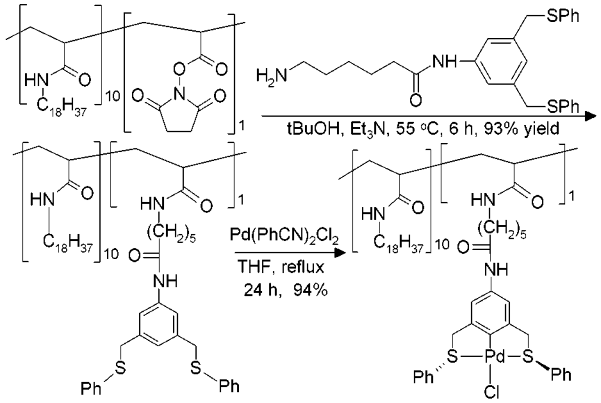
Scheme 1. Synthesis of a PNODAM-Bound SCS−Pd(II) Catalyst (PNODAM-5) for Use in Heck Chemistry

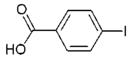
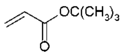
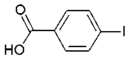
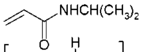
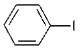
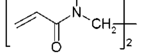
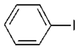
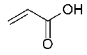
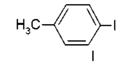
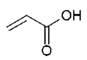
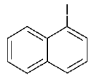
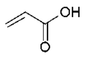


experiment with PNODAM-**3** and a pH 8 aqueous EtOH solution containing 8.5 ppm of $Ni(OAc)_2$ led to >99.4% of the Ni(II) being sequestered in the heptane phase of the penultimate biphasic heptane/aqueous EtOH mixture (<50 ppb of Ni(II) in the aqueous EtOH).

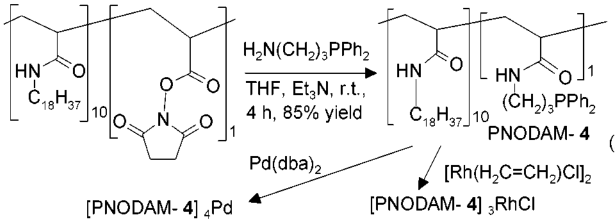
These experiments show that PNODAM-bound ligands and metal complexes are selectively soluble in the nonpolar phase of a thermomorphic biphasic mixture and that PNODAM-bound ligands effectively complex metals. PNODAM is therefore likely to be as useful for catalyst recovery as the PNIPAM ligands we used previously.[7,10,11] We verified this using PNODAM to support an air- and heat-stable SCS−Pd(II) Heck catalyst[12,13] prepared as shown in Scheme 1. The PNODAM-bound SCS−Pd(II) catalyst was characterized by solid-state ^{13}C NMR spectroscopy (the ipso C of the SCS ligand on PNODAM-**5** appears at 152.5 δ) and by ^1H NMR spectroscopy (the benzyl protons of this ligand shift to 4.5 δ from 4.0 δ on Pd-complex formation). This polymer-bound catalyst was air stable and active in a thermomorphic heptane/*N*,*N*-dimethylacetamide mixture at 110 °C.

PNODAM-**5** was comparable in activity to a similar PNIPAM-bound SCS−Pd(II) catalyst (Table 1).[7,14] The catalyst PNODAM-**5** was used for up to nine cycles in formation of cinnamic acid from iodobenzene (GC conversion in ninth cycle was 90% at 24 h), showing that catalyst recycling was very successful.

Table 1. Heck Reactions with a PNODAM-**5** Catalyst

Aryl Iodide	Acceptor	Cycle 1	Cycle 2	Cycle 3
		89%	94%	99%
		76%	85%	83%
		82%	93%	96%
		96%	99%	99%
		83%	90%	99%
		88%	99%	

[a] Heck reactions were carried out at ca. 100 °C in a monophasic heptane/*N*,*N*-dimethylacetamide mixture using 0.2 mol % of PNODAM-**5** (see Supporting Information for a detailed procedure). [b] Yields are yields of NMR pure products.



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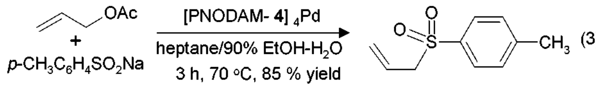

(3)

Phosphine ligands too can be bound to PNODAM to produce useful catalysts. For example, when 3 or 4 equiv of PNODAM-**4** were allowed to react with a Rh(I) or Pd(0) precursor, a solution of a PNODAM-bound Rh(I) hydrogenation catalyst or a PNODAM-bound Pd(0) allylic substitution catalyst forms (eq 2). These catalysts too could be recovered and reused in hydrogenation of a simple polar alkene like acrylic acid and in the allylic substitution reaction shown in eq 3. For example, in this latter allylic sulfone synthesis, the Pd(0) catalysts could be used through 5 cycles. However unlike the stable SCS−Pd(II) Heck catalyst, the phosphine ligands in both these Rh(I) and Pd(0) catalysts were prone to oxidation. For example, the reaction times in eq 3 had to be gradually increased from cycle 1 to cycle 5 (1 to 52 h) for complete conversion to occur. In such cases, ^{31}P NMR spectroscopy confirmed phosphine oxidation had occurred. In general, the formation of Pd or Rh metal as a black precipitate was a visual harbinger of catalyst decomposition. Such adventitious oxidation limits the utility and useful recyclability of PNODAM-bound phosphine-ligated catalysts to systems where rigorous oxygen exclusion is practical.

To summarize, polyacrylamides with hydrophobic alkyl groups are effective handles for recovery of homogeneous catalyst and sequestration of trace metals in the nonpolar phase of a biphasic solvent mixture. Ongoing work to design more active Heck catalysts on this support, to explore the phase selectivity solubility of *N*-alkylacrylamides, and to study other catalysts will be reported in due course.

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Supporting Information Available: Experimental procedures for synthesis of the PNODAM polymer and PNODAM-**2**, PNODAM-**3**, PNODAM-**4**, and PNODAM-**5** along with a typical procedure for carrying out an inverse thermomorphic Heck reaction are provided (PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

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(12) (a) Bergbreiter, D. E.; Osburn, P. L.; Liu, Y.-S. *J. Am. Chem. Soc.* **1999**, *121*, 9531−8. (b) Van Manen, H.-J.; Nakashima, K.; Shinkai, S.; Kooijman, H.; Spek, A. L.; Van Veggel, F. C. J. M.; Reinhoudt, D. N. *Eur. J. Inorg. Chem.* **2000**, 2533−40. (c) Gimenez, R.; Swager, T. M. *J. Mol. Catal. A: Chem.* **2001**, *166*, 265−73. (d) Dupont, J.; Gruber, A. S.; Fonseca, G. S.; Monteiro, A. L.; Ebeling, G.; Burrow, R. A. *Organometallics* **2001**, *20*, 171−6.

(13) Terdentate XCX catalysts of various sorts have now been described and used successfully for various transition metal-catalyzed processes, cf. (a) Albrecht, M.; van Koten, G. *Angew. Chem., Int. Ed.* **2001**, *40*, 5001−31 and (b) Morales-Morales, D.; Lee, D. W.; Wang, Z.; Jensen, C. M. *Organometallics* **2001**, *20*, 1144−7.

(14) Bergbreiter, D. E.; Case, B. L.; Liu, Y.-S.; Caraway, J. W. *Macromolecules* **1998**, *31*, 6053−6062.