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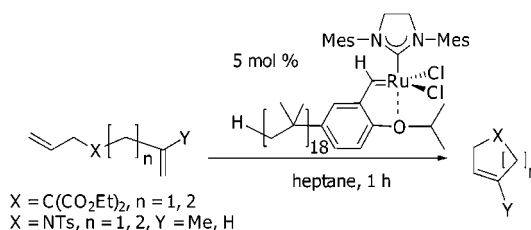
Chayanant Hongfa,[†] Jianhua Tian,[†] Hassan S. Bazzi,^{*,‡} and David E. Bergbreiter^{*,†}

Department of Chemistry, Texas A&M University, College Station, Texas 77842-3012,
and Department of Chemistry, Texas A&M University at Qatar, P.O. Box 23874,
Doha, Qatar

bergbreiter@tamu.edu; bazzi@tamu.edu

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ABSTRACT



Terminally vinyl-functionalized polyisobutylene (PIB) oligomers can be easily transformed into end-functionalized PIB-bound Ru metathesis catalysts. The nonpolar catalysts so prepared can be used as solutions in heptane and recycled by a gravity-based extraction after addition of a heptane-immiscible polar solvent. This paper describes the synthesis and the recycling of a PIB-supported second-generation Hoveyda–Grubbs catalyst for Ru-catalyzed ring-closing metathesis and ring-opening metathesis polymerizations.

Ruthenium-catalyzed ring-closing metathesis, cross metathesis, and ring-opening metathesis polymerization have developed into broadly useful methodology.¹ These homogeneously catalyzed reactions are equally useful in complex syntheses and in the formation of materials. However, as is true for other homogeneously catalyzed reactions, strategies to recover and reuse catalysts are of interest. For these Ru catalysts, these strategies include using soluble polymers, insoluble polymers, and boomerang insoluble polymer-supported catalysts.² Water and scCO₂ soluble ligands that enable catalyst use or recovery in environmentally benign

solvents have been developed.³ Ionic liquids have also been used to recycle catalysts.⁴ Here we describe an alternative approach using a heptane-soluble polymer to prepare a second-generation Hoveyda–Grubbs catalyst that is recoverable and reusable in hydrocarbon solvents by liquid/liquid or liquid/solid separations after catalysis.

Two strategies are possible with a heptane-soluble catalyst. First, a catalyst selectively soluble in a heptane-rich phase of a liquid/liquid biphasic mixture can be recovered in that phase after a monophasic reaction. This can be done by using thermomorphic or latent biphasic conditions or by product extraction with a heptane-immiscible solvent.⁵ A second approach is to simply carry out the reaction in heptane and to rely on the fact that many polar organic products are not

[†] Texas A&M University.

[‡] Texas A&M University at Qatar.

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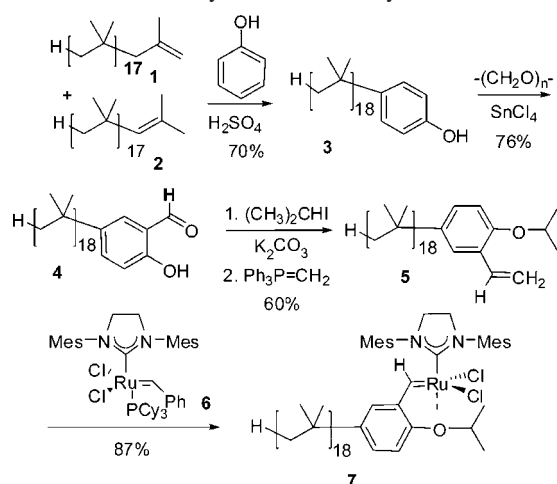
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especially soluble in heptane. If such a product were a solid, filtration or decantation can then separate the catalyst and product. Both approaches are described below.

The general strategy for synthesis of a heptane-soluble metathesis catalyst relied on the use of commercially available vinyl-terminated polyisobutylene. While this material can be >90% =CH₂ terminated polyisobutylene **1**, some samples contain as much as 20% of the internal double bond (e.g., polyisobutylene **2**). A Friedel–Crafts alkylation of either structurally isomeric polyisobutylene oligomer, however, yields the same 4-(polyisobutyl)phenol product **3**.⁶ Formylation of this oligomeric phenol by using paraformaldehyde produces the 2-hydroxy-5-(polyisobutyl)benzaldehyde **4**. This product can in turn be converted into the oligomeric styrene derivative **5** by using a Wittig olefination. Exchange of the methylene group with the benzylidene group of the commercially available second-generation Grubbs catalyst **6** produced the desired heptane-soluble catalyst **7** (Scheme 1). The last step of this synthesis also used flash

Scheme 1. Synthesis of a PIB-Supported Second-Generation Hoveyda–Grubbs Catalyst



column chromatography to separate the PIB-bound Ru complex **7** from starting materials. Chromatography is not usually used in the synthesis of polymer-bound catalysts but is feasible for **7** just as it is feasible for PEG-bound or dendrimer-bound catalysts.^{2c,3b} As is the case for other terminally functionalized polymer-bound ligands/catalysts, all of the intermediates in these syntheses could be characterized by ¹H NMR spectroscopy.^{6–8} Figure 1 illustrates the sort of ¹H NMR spectra that can be obtained for species like catalyst **7**. This spectrum establishes that catalyst **7** like its low molecular weight analogue involves the isopropoxy group in the Ru coordination sphere as the heptet due to the

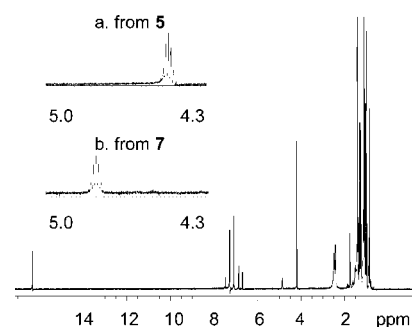
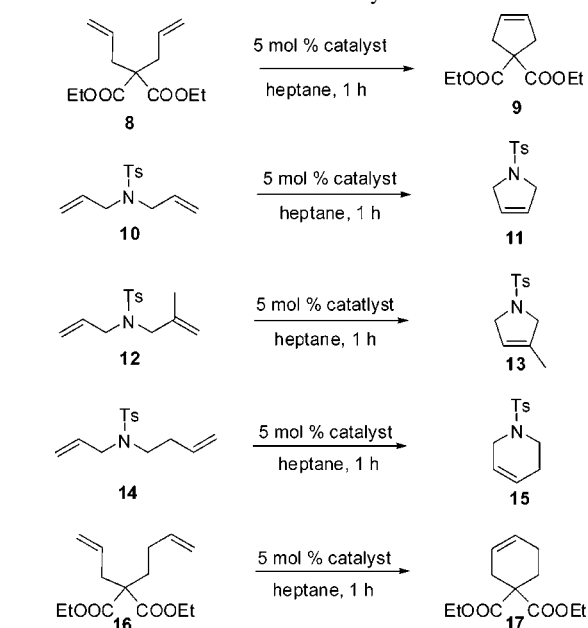


Figure 1. ¹H NMR spectrum of a polyisobutylene-bound ruthenium metathesis catalyst **7** showing changes in the *i*-Pr heptet in inset a and b for **5** and **7**, respectively.

CH of the isopropoxy shifts from δ 4.51 in **5** to δ 4.87 in **7** (cf. Figure 1, insets a and b).

Other than having a polyisobutylene-containing ligand that makes it heptane soluble, the catalyst **7** was unexceptional in its reactivity, converting a variety of α,ω -dienes into cyclic olefins at room temperature (Table 1). The catalyst could be recycled multiple times. The recycling of **7** was accomplished several ways. The most standard approach used

Table 1. RCM Reactions with Catalyst **7**^a



product	cycle 1	cycle 2	cycle 3	cycle 4	cycle 5
9	66%	75%	75%	94%	99%
11	72%	81%	94%	98%	98%
13	84%	84%	93%	99%	99%
15	67%	76%	84%	84%	93%
17	62%	70%	80%	88%	96%

^a Yields in cycles 1–5 are of products isolated by solvent removal and increase cycle to cycle because of saturation of the heptane phase by products.

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for dienes like **8** and **16** was to carry out the reaction in heptane as a solvent and to then extract the product with acetonitrile. In such cases, the less dense heptane phase contained the catalyst **7** and recycling simply involved addition of fresh substrate.

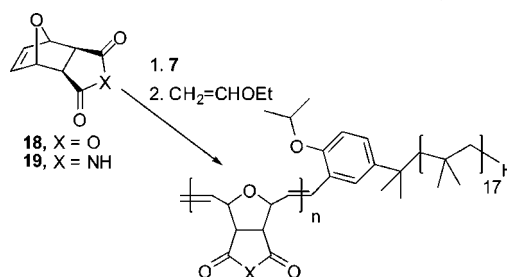
While catalyst **7** was in our experience equivalent in reactivity to the commercially available **6**, its heptane solubility and the generally poor solvating ability of heptane toward many polar organic products makes another recycling scheme possible. For example, using the substrates **10**, **12**, and **14** in Table 1, we were able to carry out a reaction through at least five cycles by simply adding a heptane-soluble starting material to the heptane solution of the catalyst. After 1 h, the heterocyclic product precipitates from heptane leaving a solution of the catalyst that can be separated by forced siphon and reused. The apparent increases in yields from cycles 1–5 in Table 1 reflect saturation of the heptane phase by products.⁹ If a catalyst were used through multiple cycles this would pose little problem unless the product or byproducts were heptane soluble.^{9b}

The efficiency of separation of catalyst and product was evaluated by ICP-MS analysis, using a sample of product **9** and **11** from the first and third reaction cycles of a cyclization like that of Table 1. Combustion of product **9** and digestion of any residue in concentrated sulfuric acid showed the presence of ca. 20 ppm Ru in the product phase. This translates into recovery of ca. 97% of the Ru for a second cycle. The loss of Ru presumably reflects the fact that the present scheme requires the Ru-methylidene intermediate formed from **7** to be recaptured by **5** formed in situ for complete Ru recovery. Inefficiencies in this process and loss of Ru to another phase are most notable in the higher level of Ru contamination in experiment where **11** precipitated from heptane. In this case, ca. 96% of the Ru catalyst was still recovered, but the solid product contained ca. 1000 ppm of Ru. This high concentration of Ru is due to the small volume of the product phase and partitioning of Ru species onto the small volume of the polar solid that is formed. This suggests that designing other systems where the Ru species

in the catalytic cycle always has a hydrocarbon soluble ligand may lower Ru leaching.

The reactivity of catalyst **7** was also tested in ring opening-metathesis polymerization (ROMP) reactions.¹⁰ In this case, the use of **7** is expected to generate an amphiphilic block copolymer since the ligand's PIB chain will be the end group of the product polymer chain. The ROMP reactions of **18** and **19** with catalyst **7** were studied in THF at room temperature (Scheme 2), using a monomer:initiator ratio of

Scheme 2. ROMP Reactions with Catalyst **7**



30:1. ^1H NMR showed quantitative conversion in both reactions after 20 min. The reactions were then quenched with ethyl vinyl ether, and the resulting polymers were isolated. Catalyst **7** is thus useful in RCM or ROMP chemistry.

In summary, the studies here show that polyisobutylene oligomers are an excellent heptane selectively soluble polymer support for the second-generation Hoveyda–Grubbs catalyst. The derivatization and chemistry of these oligomers can be easily followed by conventional spectroscopy. The activity of the PIB-supported catalyst is analogous to that of other soluble polymer or nonsupported catalysts.

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Supporting Information Available: Experimental procedures and characterization data for the synthesis of PIB-bound ligands and catalyst **7** and procedures for the ring-closing reactions and ring-opening polymerization reactions. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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