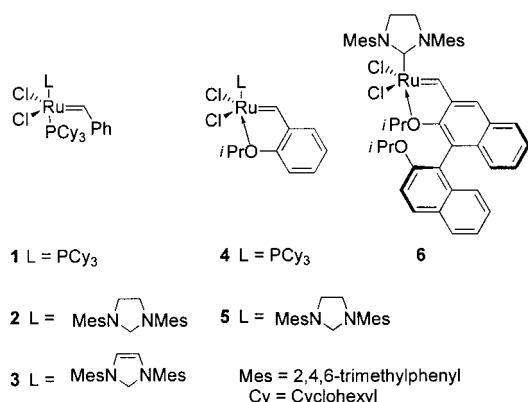


A Self-Generating, Highly Active, and Recyclable Olefin-Metathesis Catalyst**

Stephen J. Connon, Aileen M. Dunne, and Siegfried Blechert*

As the world becomes more cost-conscious and environmentally aware, the pursuit of new transition-metal catalysts that are both active and recyclable has become increasingly important to synthetic organic chemists. Recently, the advent of efficient homogeneous ruthenium alkylidene precatalysts **1–6**^[1] have propelled the olefin-metathesis reaction to the



forefront of contemporary organic chemistry as a mild and efficient method for C–C-bond formation.^[2] Given this new-found significance, it is not surprising that the development of reusable catalysts has been the goal of a number of research groups.^[3,4]

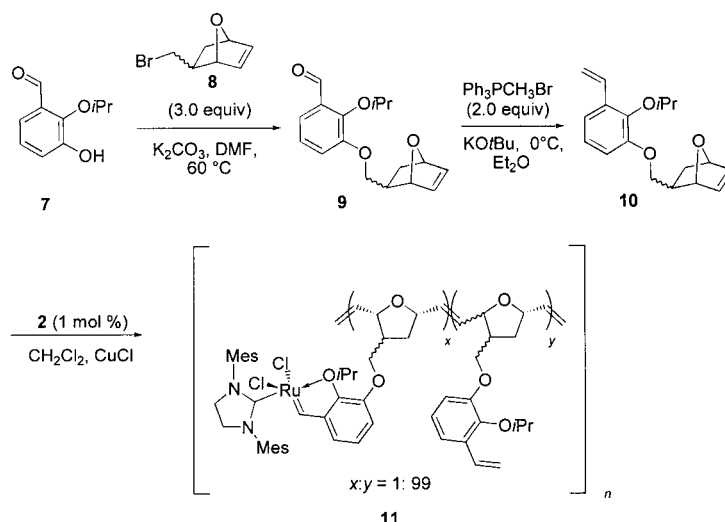
Various recycling strategies have been reported:

- Recovery of the homogeneous catalyst by chromatography of the crude reaction mixture^[1c,d]
- Filtration of the reaction mixture to separate the heterogeneous catalyst bound to a polymeric solid support^[3a–c,g–j]
- Selective precipitation of the homogeneous catalyst from solution after the reaction.^[3f]

Chromatographic recovery furnishes pure catalyst for reuse, but is time-consuming and generates considerable amounts of silica and solvent waste. Heterogeneous catalysts are easily recovered with minimal waste, however with one reported exception^[3i] these catalysts are much less active than their homogeneous counterparts. By employing a selective catalyst-precipitation strategy, one can

aspire to preparing ruthenium alkylidenes with reactivity profiles that correspond to those of homogeneous catalysts, combined with a facile recovery methodology that involves a simple change in the polarity of the solvent to allow easy separation of the catalyst from the substrate. The only previous report that involves this method detailed a variant of **4** attached to polyethylene glycol (PEG) chain which could be precipitated with diethyl ether.^[3f] The levels of residual ruthenium in the products is a critical issue in all heterogeneous systems. We report herein the design and preparation of a polymer-bound, homogeneous, recyclable, and highly efficient ruthenium catalyst. The polymer support also seems capable of scavenging ruthenium after the reaction, thus allowing the formation of metathesis products that contain extremely low ruthenium levels.

It is known that ring-opening-metathesis polymerization (ROMP) products of substituted oxanorbornene derivatives are often soluble in organic solvents with the notable exceptions of methanol, diethyl ether, or diethyl ether/hexane mixtures. This led us to postulate that a ruthenium alkylidene incorporated into these products could serve as a recyclable and easily assembled catalyst without the need for the purchase of and attachment to often expensive solid-phase resins. It was thus conceivable that **10** (Scheme 1) could serve



Scheme 1. Synthesis of catalyst **11**.

as a precursor for such a catalyst through consecutive (one-pot) ROMP and cross-metathesis (CM) attachment of the ruthenium moiety to the polymer. Compound **10** contains an isopropoxy styrene moiety necessary for catalyst formation and an oxanorbornene ring destined to become the polymer support after ROMP. Furthermore, the second ether linkage is positioned *ortho* to the chelating isopropoxy group. This is an important consideration: by correlation with catalyst **6** and from preliminary studies conducted in our laboratories, we were aware that the presence of alkoxy groups in this *ortho* position leads to catalysts that display strongly enhanced activity relative to **5**.^[1f]

Aldehyde **9** was readily prepared in good yield (76 %) by the action of the potassium salt of **7** on bromide **8** in *N,N*-

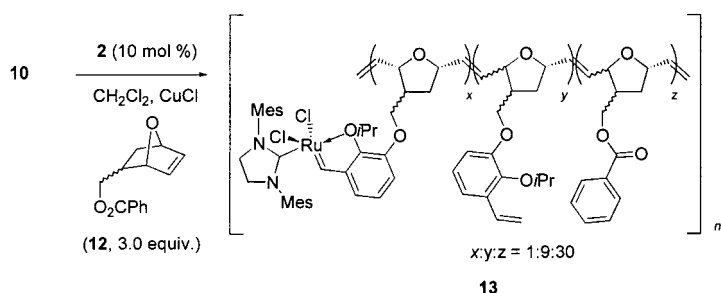
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dimethylformamide (DMF).^[5] Subsequent Wittig olefination gave styrene derivative **10** in 79% yield. Treatment of **10** with **2** (1 mol%) in CH₂Cl₂ at 20 °C in the presence of CuCl as a phosphane scavenger gave polymer-bound catalyst **11** (Scheme 1).

Catalyst **11** was tested in simple ring-closing-metathesis (RCM) reactions and gave encouraging results. Excellent conversions were obtainable for up to four consecutive cycles; however, long reaction times (7–12 h) were required for quantitative conversion. We speculated that the sluggish activity was in part due to the difficulty in forming the catalytically active 14-electron species^[6] in the presence of 99 equivalents of ligand and thus decided to lower the ligand/catalyst ratio by a factor of 10. To avoid a situation in which two catalyst moieties could exist in close proximity to one another, an oxanorbornene benzoate co-monomer **12** was added to act as a spacer. This was prepared from the same batch of alcohol used to prepare bromide **8**, and so had the same *endo/exo* isomer ratio (ca. 1:1) as styrene **10**. For ease and simplicity of catalyst preparation, no attempt was made to separate these *endo/exo* mixtures, which arise from the Diels–Alder reaction used to prepare **8**.^[5] In our experience, the rates of polymerization of these isomers do not differ greatly in any case. Thus, reaction of **2**, **10**, and **12** (1:10:30) at room temperature in CH₂Cl₂ gave quantitative polymerization of both oxanorbornene compounds **10** and **12** after 10 min to give a red solution, indicative of the presence of **2**. Addition of CuCl gave a green solution after heating at reflux for 1 h. Workup gave polymer-bound **13** in 93% yield (Scheme 2).



Scheme 2. Preparation of catalyst **13**.

Polymer **13** is soluble in most common organic solvents but not in diethyl ether and hexane. To our delight, the catalyst loading can be determined (typically in the range 0.08–0.1 mmol g^{−1}) by relative integration of the broad alkylidene signal at $\delta = 16.7$ ppm and the signal for the aromatic *ortho* proton ($\delta = 8.0$ ppm) of the benzoate moiety in the ¹H NMR spectrum (a 1:60 ratio of alkylidene/benzoate indicates quantitative ROMP and CM). Thus, expensive, time-consuming, and often inconvenient ruthenium analysis is not required. This loading indicates a high level of incorporation (i.e. efficient CM) of the ruthenium moiety onto the styrene-substituted polymer backbone, which was reproducible between polymer batches. ROMP-based catalyst **13** was found to have impressive activity in RCM, ROM-CM, and tandem metathesis reactions (Table 1).

With only 1 mol% (measurable by ¹H NMR spectroscopy) of **13** at 20 °C it was possible to generate five-, six-, seven-, and

Table 1. Activity of **13** in various metathesis reactions.

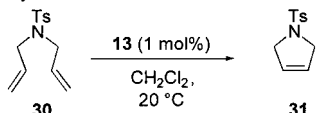
Substrate ^[a]	Product ^[b]	Conversion [%] ^[c]
		> 98
		> 98
		> 98
		> 98
		> 98
		> 98
		> 98
		> 98 ^[d]

[a] Conditions: **13** (1 mol%), CH₂Cl₂ (0.05 M), 20 °C. [b] Reaction times (min) in parentheses. [c] Determined by ¹H NMR spectroscopic analysis. [d] **13** (0.05 mol%), allyltrimethylsilane (1.0 equiv).

eight-membered rings **22–27** with quantitative conversion. The formation of trisubstituted olefin **23** and the compatibility of **13** with potentially chelating hydroxy- and amide-functionalized substrates **16** and **17** further underlines the synthetic utility of this catalyst. In all previous literature reports 2.5–5% of the polymer-bound catalyst and higher temperatures (usually 45 °C) were required to promote efficient metathesis.^[3] In the atom-economic and efficient ROM-CM reaction only 0.05 mol% of catalyst was necessary to give quantitative conversion of **21**.

Having established the reactivity of **13** under mild conditions, we then turned to the critical question of recyclability. It was found that after metathesis, **13** could be conveniently precipitated and filtered off by the addition of diethyl ether or hexane. In the RCM of *N*-tosyldiallylamine (**30**), **13** can be recycled easily under the conditions outlined previously in Table 1, with quantitative conversion for each of seven consecutive cycles (Table 2).

Table 2. Recyclability of **13** in the RCM of **30**.



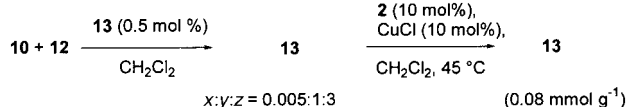
Cycle	<i>t</i> [h]	Conversion [%] ^[a]
1	1	> 98
2	1	> 98
3	1	> 98
4	1	> 98
5	1	> 98
6	2	> 98
7	4	> 98
8	72	75

[a] Determined by ¹H NMR spectroscopic analysis.

Total-reflection X-ray fluorescence (TXRF) analysis^[7] of the products after catalyst separation indicated that a maximum of 0.004 % ruthenium was present in each of the first four cycles. This value is approximately an order of magnitude lower than that of contemporary literature systems for the removal of ruthenium after the reaction^[3,8] and even two orders of magnitude lower than that of the best previously reported polymer-bound catalysts.^[3] It seems likely, therefore, that ruthenium remains attached to the polymer even after catalyst deactivation. Importantly, a ruthenium-saturated analogue of **13** (i.e. all styrene moieties loaded) was considerably less recyclable under these conditions, thus indicating that the recyclability of **13** is largely due to the presence of an excess of Lewis basic ligand, which captures the catalytically active species after the reaction. When the small amount of ruthenium used (1 mol% over seven cycles) is taken into account, **13** compares very favorably in terms of recyclability with literature systems.^[3] In addition to being more recyclable, **13** displayed a much enhanced metathesis activity relative to **5** in the RCM of **30**,^[9] and was comparable in terms of reaction rate to benchmark catalyst **2**. For example, in the RCM of **30** at high dilution (0.01 M, CH₂Cl₂, 20 °C, in air) the time taken to reach 80 % conversion to **31** was 65 min in the presence of **13**, whereas to 119 min were required when using non-polymer-bound catalyst **5**.^[9]

Given the mode of formation of **13**, it seemed likely that a high degree of self-generation of the polymer support would be possible. As expected, when just 0.5 mol % of **13** was added to a solution of **10** and **12** (1:3) in CH₂Cl₂, polymerization was complete after 10 min to afford **13** (off-white color) and no signal for the alkylidene was observed in the ¹H NMR spectrum. This ruthenium-deficient version of **13** could then be loaded with commercially available **2** to a preselected level under standard conditions (Scheme 3). It is envisaged that this development will allow greater control of the catalyst-loading process.

In summary, we have developed a highly efficient and recyclable ROMP-based catalyst,^[10] which combines good



Scheme 3. Self generation of the polymer support.

solution-phase activity with high and convenient recyclability without requiring the purchase of often expensive solid-support resins. The catalyst is prepared from inexpensive starting materials in a straightforward manner; the generation of the solid-support and attachment of the ruthenium moiety is possible in *one* convenient step through sequential ROMP and CM. The products from metathesis reactions involving these catalysts also contain unparalleled low levels of residual ruthenium. The conceptually novel catalyst **13** represents a balance between the high activity of suitably substituted analogues of **6**, and the recyclability of **5**; possible through ligand design and stoichiometry.

Studies on the exploitation of these flexible systems in new metathesis applications are underway. One example is the incorporation of a modified fluorescence marker into the catalyst to identify trace quantities of polymer in the reaction products. Investigation of the product by mass spectrometry is another option. The results of these and other investigations will be reported in due course.

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