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Ruthenium Removal Using Silica-Supported Aromatic Isocyanides

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ABSTRACT

New silica gel scavengers containing aromatic isocyanides have been synthesized and evaluated for Ru removal. A thiol-ene click reaction was used to attach the isocyanide precursor to a thiol-containing siloxane. Conventional methods for grafting to silica gel at elevated temperature resulted in significant hydrolysis of the isocyanide. A novel cleavage reaction was developed to quantitate the amount of surface-loaded isocyanide. Binding by the new materials was comparatively evaluated for a variety or Ru carbene catalysts. The optimal conditions were extended to two ring-closing metatheses (RCM). The residual Ru was determined by inductively coupled plasma mass spectrometry (ICP-MS). For facile RCM reactions, the UV data agreed with the ICP-MS results. However, more difficult RCM did not correlate well with the UV data. This was interpreted in terms of varying extent of catalyst decomposition. In all cases, isocyanide scavenger reagents were found to be superior to commonly used, silica gel-based metal scavengers.

1. Introduction

From a sustainability and cost perspective, removal and recovery of metal catalysts from crude reactions is significant for the recycling of precious metal catalysts. For the organic or medicinal chemist, recovery of the metal also facilitates purification of the organic products which may need to be completely metal free for biological studies. Even within families of catalysts like Ru carbenes (Grubbs catalysts) and Pd-phosphine complexes, variation of ligands can dramatically alter reactivity with organic substrates and scavenger materials. Not surprisingly, a wide range of scavenger agents have emerged to address this problem. In particular, silica gel-supported reagents are desirable due to their low cost, robustness and ease of retrieval. At the end of a reaction, the starting metal catalyst ends up as several different species, so an effective scavenger must capture all of these. Effective scavengers can also be used as quenching agents in the best cases by rapidly arresting a chemical reaction to facilitate the analysis of reaction mixtures and for kinetic studies. Understanding the rate of scavenger binding helps with the selection of the appropriate metal scavenger.

We recently developed isocyanides as scavengers for late transition metals such as Pd and **Ru** [1]. Isocyanides are strongly binding ligands which are isoelectronic to CO. We found that these pi-acid ligands arrested metathesis reactions instantly and caused a Buchner reaction in Ru carbene complexes [2]. The silica-supported reagent, **B**, containing an alkyl isocyanide, proved effective for the removal of Pd in cross couplings. Both **Ru [1a]** and **Pd [1b]** could be removed to ppm levels, usually with only a filtration step (Scheme 1a). Subsequently, Grela and co-workers developed soluble isocyanides for similar purposes (Scheme 1b) [3]. These tertiary amine-containing isocyanides were shown to react with a variety of Grubbs catalysts to form highly polar isocyanide-Ru complexes. The most studied tertiary amine-containing scavenger, **C**, was shown to effectively remove Ru to ppm levels from a ring-closing metathesis (RCM). [3a] Though soluble isocyanides are effective, the need exists for improved solid-supported reagents, since simple bed filtration is a validated and scalable process that is used in industry. Simple filtration is an attractive purification step for any metal-catalyzed reaction.

Previously reported kinetic analysis of a Buchner reaction found that aryl isocyanides reacted faster than alkyl isocyanides [4]. Aryl isocyanides have optimal σ donor / π acceptor properties which allow rapid binding to the Ru and result in a fast Buchner reaction.

Since a diverse array of Grubbs catalysts are used for catalytic olefin metathesis applications, the ideal metal scavenger must work effectively for them all, or it must be delineated which combinations of catalyst and scavenger are best. The Hoveyda-Grubbs type precatalysts (**Ru1-6**), indenylidene-containing catalysts, (**Ru2, Ru8-10**) and the Grubbs catalyst (**Ru7**) were studied to determine how structural effects impacted the effectiveness of Ru removal using silica-supported aromatic isocyanides (Scheme 2).

In this work, new silica gel scavengers containing aromatic isocyanides were evaluated for Ru removal from a range of commonly used Grubbs metathesis catalysts. A motivation of this work was to develop a faster screening assay to find optimum combination

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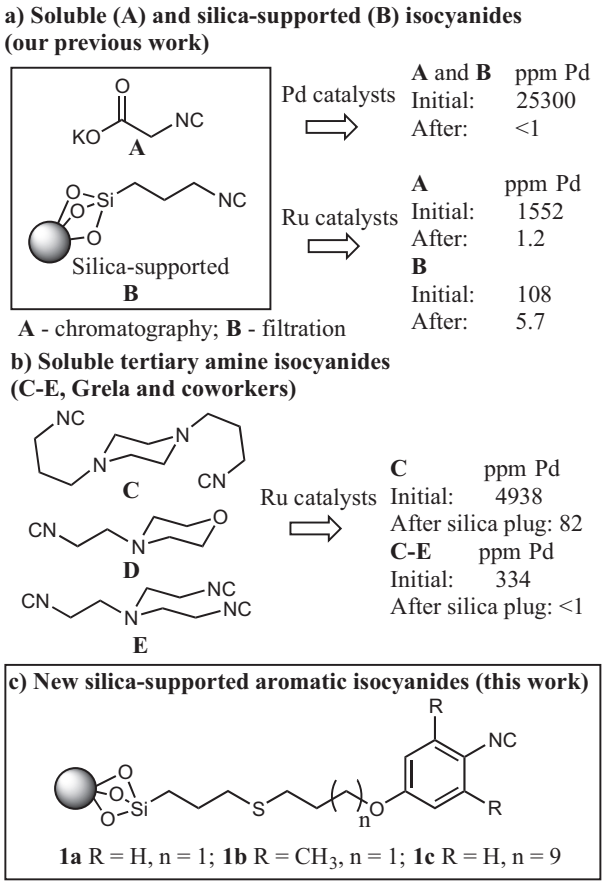
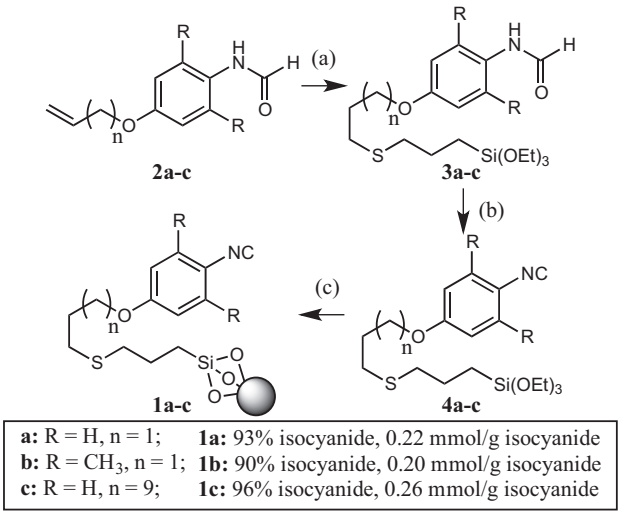


Scheme 1. Soluble, supported and new isocyanide-based scavengers for Ru removal from catalytic reactions such as ring-closing metathesis (RCM).

of scavenger and metal catalyst. In the grafting process, hydrolysis was found under standard grafting conditions. This required a new procedure to quantitate isocyanide and with this, grafting conditions were optimized. Ultimately, the results from the UV assay allowed for the selection of the best scavenger materials which were



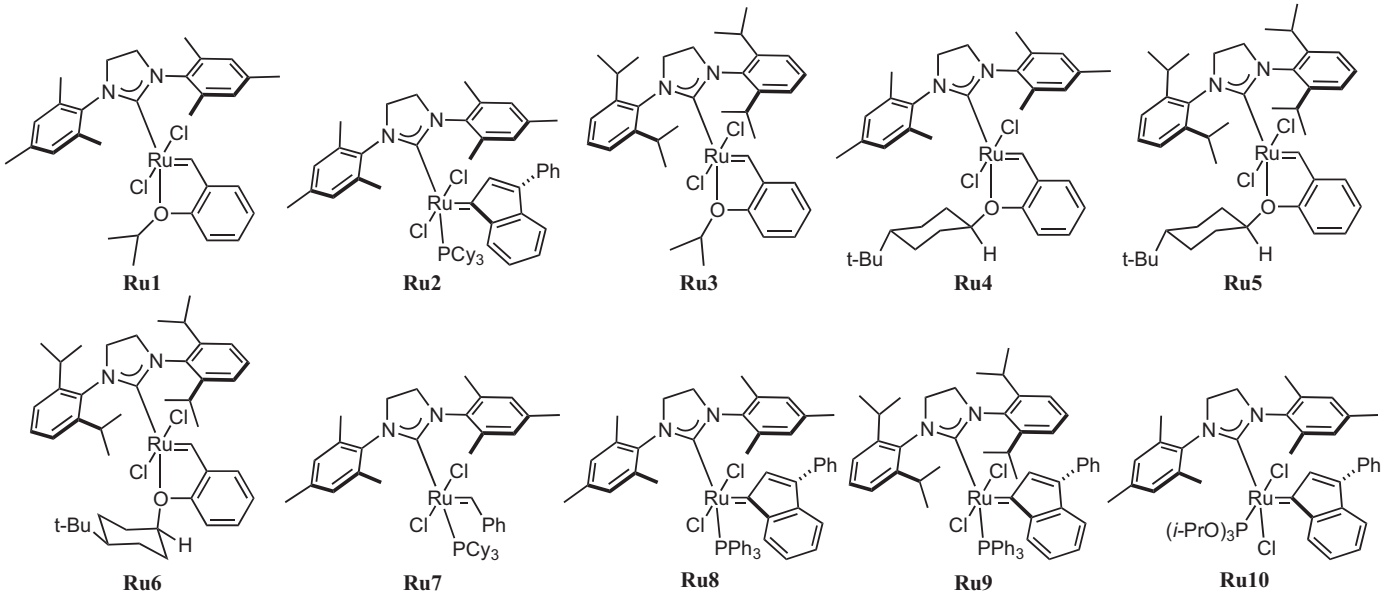
Scheme 3. Synthetic scheme and intermediates for silica-supported aryl isocyanides.

then used for Ru removal from two catalytic ring-closing metathesis reactions (RCMs), which were quantitated by inductively coupled plasma-mass spectrometry (ICP-MS). Overall, we found that the new isocyanide materials were highly effective scavengers and the developed UV assays were useful for reaction optimization and for the comparison of materials, but these assays alone could not quantitatively predict the effectiveness of Ru removal.

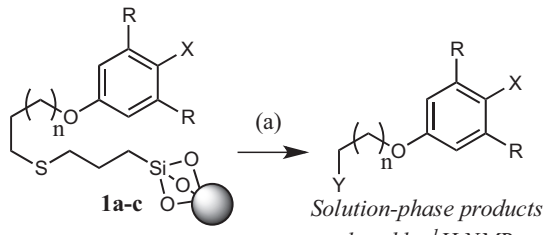
2. Results and Discussion

2.1. Synthesis of materials

Silica-supported isocyanides were synthesized by a scalable thiol-ene reaction (Scheme 3). In all cases, 3-mercaptopropyltriethoxysilane served as the thiol, which could be grafted to the silica surface. Aryl formamides **2a-c** bearing pendant



Scheme 2. Ru carbenes analysed by UV and ICP-MS assays.



X = NC or NCHO; Y = SCN or Br

Conditions: (a) 1) crushed 4 Å mol. sieves, CD_3CN, rt, overnight; 2) BrCN, CD_3CN, 60 °C, 2 h

Scheme 4. Cyanogen bromide cleavage of thioethers.

alkenes were the partners for the click reaction. Following the procedure of Garrell and co-workers, [5] the thiol and alkene were coupled to give quantitative yields of thioethers **3a-c**. A subsequent dehydration step provided isocyanides **4a-c** in good yields after chromatography. Last, grafting siloxane monomers onto silica, followed by extensive washing, gave the silica-supported materials **1a-c**.

2.2. Determination of isocyanide loading

Pure isocyanides **4a-c** were grafted onto silica gel, however the silica-supported materials **1a-c** were found to contain a mixture of isocyanide and formamide. Diffuse Reflectance Infrared Fourier Transform spectroscopy (DRIFT IR) provided a qualitative assessment of isocyanide purity (Fig. 1). Analysis of silica gel materials by DRIFT-IR showed the presence of the isocyanide and formamide functional groups at 2125 cm^{-1} and 1678 cm^{-1}, respectively. Comparison of isocyanide **1a** grafted at 25 °C (Fig. 1a), 80 °C (Fig. 1b), and formamide **5a** (Fig. 1c) showed an increasing formamide signal with increased grafting temperature. The recovered (ungrafted) isocyanides **4a-c** were found to be pure with no hydrolysis to the formamide. The undesired surface-bound formamide was formed by silica-catalyzed hydrolysis of pure isocyanides with more hydrolysis occurring at higher temperatures. Improved isocyanide purity was obtained by grafting at room temperature.

The standard literature method for quantification of solid-supported isocyanides is through elemental analysis for nitrogen [6]. This assumes that all nitrogen is present as one functional group, which is not accurate when hydrolysis occurs since %N represents a composite of isocyanide and formamide. No satisfactory method exists in the literature to solve this problem.

To determine the isocyanide loading, isocyanides **1a-c** were cleaved from silica using cyanogen bromide. Cyanogen bromide cleavage of thioethers is known as the von Braun reaction [7]. Thioether activation by cyanogen and subsequent S-C bond cleavage by the bromide nucleophile resulted in monomer detachment, thereby allowing quantitative analysis of the soluble products by ^{1}H NMR; see Scheme 4 and Figures S1 and S2 [8]. Combination of N elemental analysis with the measured isocyanide and formamide ratio enabled calculation of the isocyanide loading. Triplicate analysis of a freshly prepared batch of **1a** found 93 ± 4% isocyanide and 0.32 mmol/g N loading; therefore, the isocyanide loading was calculated to be 0.30 ± 0.01 mmol/g [9].

2.3. Rate of binding by aromatic isocyanides

To determine the optimal time for Ru binding by isocyanides, we monitored the reactions of two commercially-available Ru carbenes with soluble isocyanides. In situ FT-IR was used to compare the relative binding kinetics of soluble isocyanides **4a** and **4b** with **Ru1** and **Ru2** [10]. Consumption of the ν(C≡NAr) absorbance at 2120 cm^{-1} resulted in the formation of a new Ru-C≡N isocyanide stretch between 2098-2109 cm^{-1} (Fig. S5). Treating 3 equiv isocyanides with Ru carbenes then monitoring the formation of Ru-isocyanide complex provided insight into relative reactivity rates (Fig. 2 and Fig. S6). For **Ru2**, a modest difference in rate was seen in the first 15 min at 0 °C, and no difference was seen at room temperature. Although **4a** and **4b** are sterically unique, there was only a minor difference in reactivity between these isocyanides.

Table 1
Stability of Ru carbenes on silica gel.

Entry	RuX	Percent bound[a]
1	**Ru1**	8 ± 3[b]
2	**Ru2**	3
3	**Ru3**	-1
4	**Ru4**	4
5	**Ru5**	2
6	**Ru6**	1
7	**Ru7**	70 (76)[c]
8	**Ru8**	38
9	**Ru9**	71 (94)[c]
10	**Ru10**	93

2.4. UV Binding studies and comparisons of new materials

Following kinetic analysis by in situ FT-IR, we developed a UV assay to monitor the reaction of silica-supported isocyanides. Fig. S8 shows the time course of **Ru1** removal up to 2 h using isocyanide **1a** as determined by UV. To rapidly analyze binding, we treated a measured amount of silica-supported material with a 2 mM stock solution of **RuX** at room temperature for 30 min. Reactions were subsequently filtered and the solids were washed extensively to verify that all changes in precatalyst concentration were due to ligation and not due to adsorption onto silica gel. An appropriate dilution was performed and samples were analysed by UV to determine the difference of precatalyst concentrations in a treated and non-treated sample. By measuring solution concentrations of the remaining unbound metal complex we can indirectly arrive to the percent bound by the difference from the initial and final solution concentration of the metal complex.

Control studies showed that untreated silica gel accounted for removal of some Ru complexes. Of the ten **RuX** tested, we found **Ru1-6** were stable to silica and **Ru7-10** were unstable (Table 1). To our knowledge, the role of untreated silica gel in Ru removal has not been previously documented. Stable Ru complexes (**Ru1-6**) were chosen for further analysis so background binding by silica would not obscure metal removal by the isocyanide.

The general procedure for UV assays was performed with 25 mg silica gel.[a] Percent bound was calculated as [1-(concentration **RuX** in sample / concentration **RuX** in non-treated sample)] x 100%, where concentrations were determined through a standard curve. [b] Average and standard deviation of three trials using different stock solutions. [c] Results from two absorbance values.

Initially, UV analyses of **Ru1-2**, commercially-available scavengers **7-10**, formamide **5a**, and isocyanides **1a-c** were performed (Fig. 3). **Ru1** and **Ru2** were chosen because they are widely used and are the least and most sterically encumbered ruthenium carbenes used in this study, respectively. Analysis of Ru carbene binding efficacy was performed using 1, 2, and 4 equiv of scavenger for 30 min treatments.

Overall, the isocyanides were highly effective at Ru binding relative to commercially-available scavengers. Treatment of **Ru1** (Fig. 3a) with 4 equiv of commercial scavengers **7-10** did not result in complete binding, but the same condition afforded at least 94%

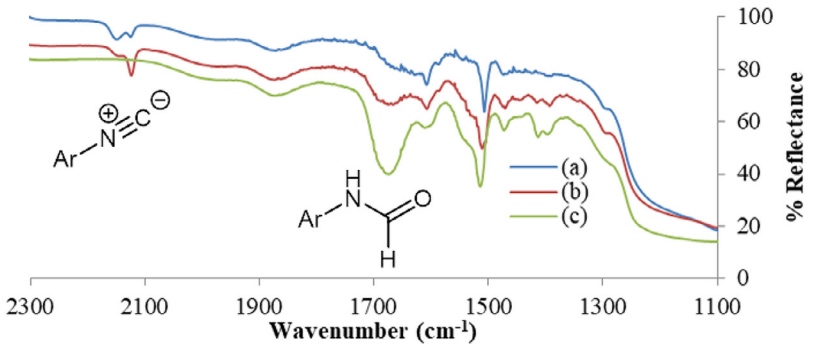


Fig. 1. DRIFT IR of silica gel material **1a** produced by grafting at (a) 25 °C, 94% isocyanide, (b) 80 °C, 45% isocyanide, and (c) silica-supported formamide, **5a**.

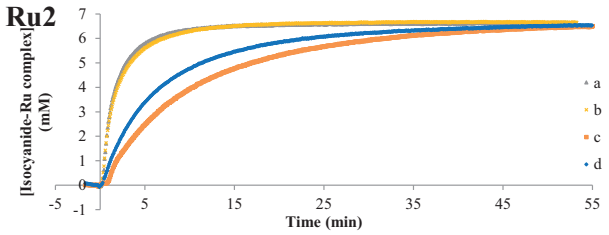


Fig. 2. In situ FTIR analysis of Ru carbene binding by solution-phase isocyanides. Entries a, b, c, and d correspond to reactions of **4a** at 23.5 °C, **4b** at 23.5 °C, **4a** at 0 °C, and **4b** at 0 °C.

metal binding for all isocyanides **1a-c**. New isocyanide silica gels were able to bind more **Ru1** with 2 equiv scavenger than the commercial scavengers bound with 4 equiv scavenger. The formamide, **5a**, did bind 17% of **Ru1** when 4 equiv were used, which may be due to the presence of the thioether. The steric environment on the aryl isocyanide and linker length had minimal effect on relative binding for **1a-1c**.

The different profiles between Fig. 3a and 3b show the effect of Ru ligand environment on isocyanide-Ru bonding. Treatment of bulkier **Ru2** (Fig. 3b) with 4 equiv of the commercial scavengers **7-10** resulted in less than 8% binding for all scavengers, whereas at least 76% of **Ru2** was bound using isocyanides **1a-c**. Treatment with 1 equiv isocyanides **1a-c** resulted in greater than 15% binding; therefore 1 equiv isocyanide is more effective than 4 equiv of standard scavengers 7-10 in all cases. The 2,6-dimethyl substituted isocyanide **1b** was slightly less effective than the unsubstituted aryl isocyanide **1a**. By contrast, the longer linker length of 1c resulted in slightly improved metal binding.

Comparison of Ru carbene binding by isocyanides **1a-c** is provided in Fig. 4. All isocyanide materials were highly effective for the removal of Ru carbene complexes from solution [11].

Binding efficacy among new aryl isocyanide materials was compared at 2 equiv isocyanide relative to Ru complex (center horizontal lanes in Fig. 4a-c). Since treatment of **Ru1** and **Ru3-6** with 4 equiv of isocyanides **1a-c** resulted in >92% binding, we examined lower loading to tease out structure-activity relationships. The 2,6-dimethyl substituted aryl isocyanide **1b** showed little reactivity difference compared to **1a**; see Fig. 4a (2 equiv) and Fig. 4b (2 equiv). Isocyanide **1c** was generally less effective, but for **Ru2** the longer linker resulted in superior performance (Fig. 3b). This could be due to better multivalent binding possible with longer or more flexible linkers. Overall isocyanides **1a** and **1b** had generally similar reac-

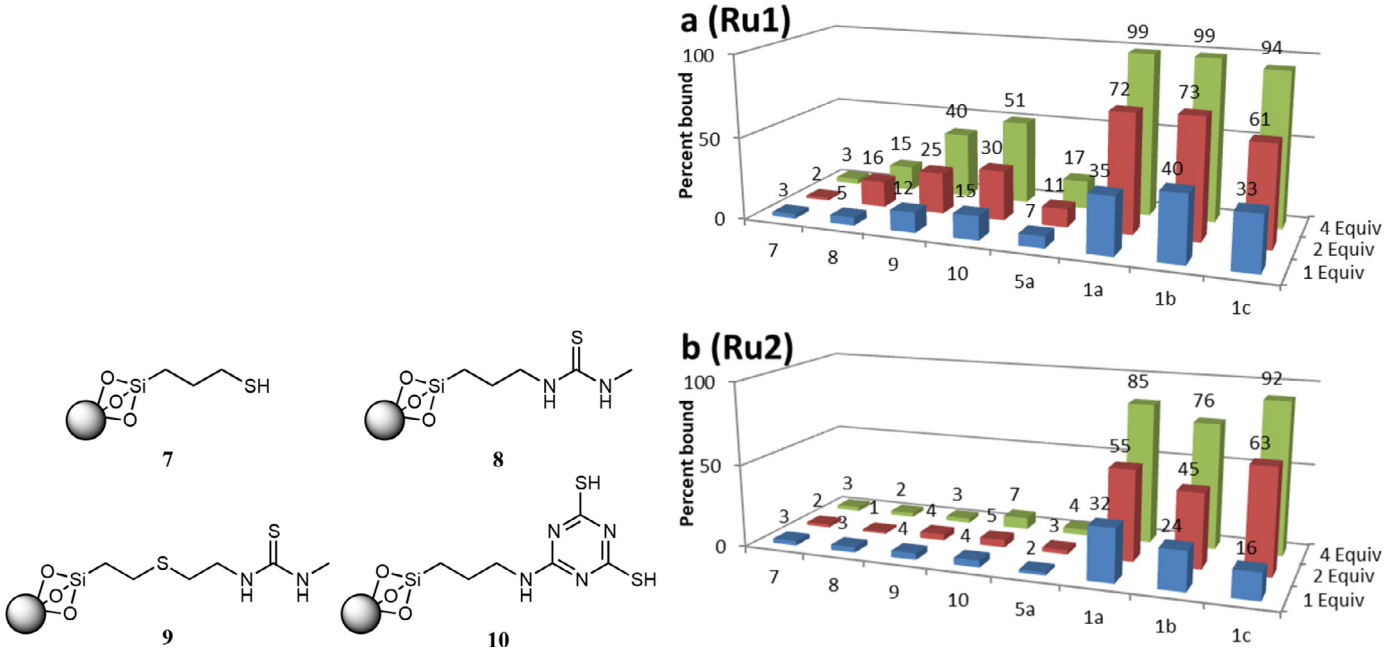


Fig. 3. UV analysis of Ru carbene binding by silica-supported materials. Panels a and b are results with **Ru1** and **Ru2**, respectively.

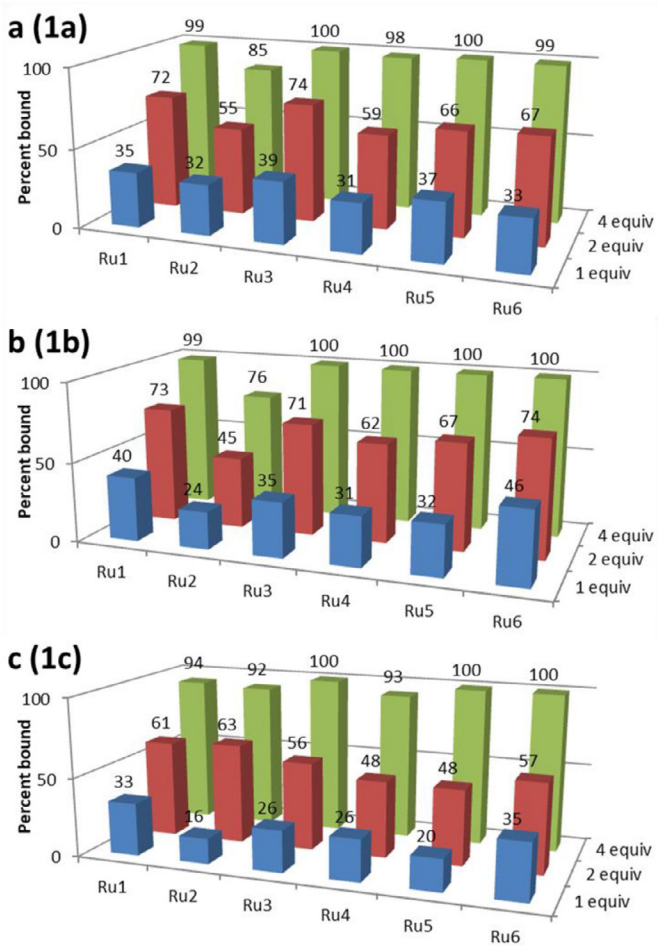


Fig. 4. UV analysis of Ru carbene binding by silica-supported isocyanides. Panels a, b, and c are results of **Ru1-6** with isocyanides **1a**, **1b**, and **1c**, respectively.

tivity and higher efficacy than 1c, but 1c was more effective for binding **Ru2**.

Treatment of the most sterically unique Ru carbenes studied (**Ru1** and **Ru2**) with metal scavengers demonstrated that more hindered Ru atoms can have reduced scavenger binding. Steric bulk impacted the effectiveness of commercial scavengers **7-10** more than isocyanides **1a-c**; see Fig. 3 above. Differences in NHC steric demand, H_2IMes (**Ru1**) versus H_2DIPP (**Ru3**), had little effect on the isocyanide efficacy. For the H_2DIPP series, the equatorial (**Ru5**) and axial (**Ru6**) cyclohexane-containing Ru carbenes showed slightly improved binding for the faster-initiating precatalyst Ru6 (Fig. 4c). DRIFT IR of a reacted isocyanide suggests the presence of multiple isocyanide species (Fig. S9).

2.5. Correlation of binding results with performance in ring-closing metathesis reactions

To correlate the results of our UV binding assays with actual metal removal, we performed two different ring-closing metatheses with various Grubbs complexes and scavengers, and analyzed the resulting crude product by ICP-MS. Since isocyanides **1a** and **1b** had similar reactivity profiles, only **1a** was used to examine Ru removal for the new materials. Thiourea **9** was chosen for comparison.

The RCMs of diethyl diallylmalonate (DEDAM, **11**) and diethyl di(2-methyl)allylmalonate (DEDMAM, **13**) were examined [12]. The RCM of **11** afforded quantitative conversion within 30 min under mild conditions. Conversely, the RCM of **13** is challenging due to formation of a strained, 2,2,3,3-tetrasubstituted ruthenacyclobutane intermediate, and since it requires forcing conditions, significant Ru carbene decomposition was expected [13]. When decomposition has occurred, the scavenger must remove Ru in its various forms. Contrastingly, the UV studies above were conducted on the Ru precatalyst alone with no decomposition products present.

The mild RCM of DEDAM (**11**) gives crude product **12** which was assayed for Ru impurity. Treatment of the crude reaction mixture with 4 and 8 equiv metal scavengers **1a** and **9** resulted in excellent and modest Ru removal, respectively (Table 2). Equivalents of scavenger is based on the Ru catalyst loading; e.g. 4 equiv corresponds to 4 mol % for 1 mol % catalyst loading. One mol % of Ru catalyst corresponds to 15422 ppm Ru in the crude organic sample after evaporation of solvent. The best result was the treatment of the crude metathesis performed with **Ru1** by 8 equiv isocyanide **1a**, where only 2 ppm Ru of the initial 15244 ppm Ru remained (Table 2, entries 1 and 3). Using the same conditions, thiourea **9** left 10091 ppm, which corresponds to 34% Ru removed (Table 2, entry 5). A similar trend was seen with **Ru4**, where treatment with 8 equiv **1a** and **9** achieved final Ru concentrations of 39 ppm and 6456 ppm, respectively (Table 2, entries 8 and 10).

The more difficult RCM of DEDMAM (**13**) gave cyclopentene **14** after a 24 h reaction time. Treatment of crude **14** with 4 and 8 equiv metal scavengers **1a** and **9** resulted in good to excellent Ru removal in all cases (Table 3) [14]. The best result for Ru removal from crude **14** was with 8 equiv isocyanide **1a**, where **Ru6** was removed to 28 ppm from an initial 9832 ppm (Table 3, entries 6 and 8). Similarly, treatment of **Ru1** with 8 equiv **1a** removed Ru to 36 ppm from 11024 ppm (Table 3, entries 1 and 3). Treatment of **Ru1** and **Ru6** with 8 equiv thiourea **9** was less effective and resulted in final Ru concentrations of 1141 and 580 ppm, respectively (Table 3, entries 5 and 10).

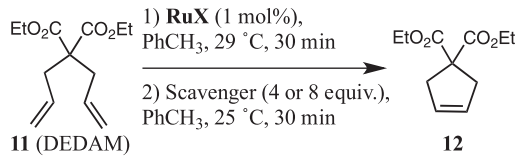
The two unique RCM reactions were performed under different conditions and resulted in different final distributions of Ru complexes and their decomposition products. The RCM performed under mild conditions (**11** to **12**) presumably had minimal decomposition products. Conversely, the more challenging RCM using forcing conditions (**13** to **14**) was expected to contain mostly decomposed Ru, with minimal to no precatalyst remaining at the end. The different Ru species present help explain the differences between the ICP-MS data and the UV experiments which used pure Ru precatalysts.

The metatheses of DEDAM (**11**) were performed under mild conditions so most Ru complexes were expected to be Ru carbenes. Since the UV binding assays were performed with only Ru carbenes, there was good correlation between the UV and ICP-MS experiments for the RCM of **11**; see Table 2 entries 2, 5, 7, 9, and 10.

The metatheses of DEDMAM (**13**) were performed using extended heating which can lead to Ru carbene decomposition. A greater fraction of decomposition products can explain the poorer correlation between the UV and ICP-MS experiments. Interestingly, the isocyanide **1a** removed residual Ru with similar effectiveness for both ring-closing metathesis; see Table 3 entries 2 and 7. Conversely, the thiourea **9** performed better in the RCM reactions than in precatalyst binding. Decomposition of the Ru carbene may expose the Ru by loss of ligands, affording improved thiourea scavenging performance.

We have demonstrated that the UV binding assay developed is a useful tool for rapid determination of relative scavenger efficacy and reaction condition optimization. Most importantly, from UV we determined that at least 4 equiv of isocyanide **1a** was required for >99% precatalyst binding. Upon treatment of crude RCM reactions with 4 and 8 equiv **1a** we observed >95% metal removal, so the UV and ICP-MS results are in agreement even though the

Table 2
Ru removal from crude **12**.

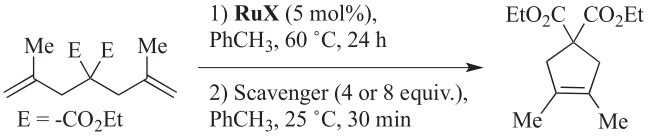


11 (DEDAM) **12**

Entry	RuX	Scavenger[a] (equiv)	[Ru] [ppm][b]	% Removal[c]	% Bound[d]
1	**Ru1**	none	15244		
2	**Ru1**	**1a** (4)	423	97	99
3	**Ru1**	**1a** (8)	2	>99	
4	**Ru1**	**9** (4)	13239	13	40
5	**Ru1**	**9** (8)	10091	34	42
6	**Ru4**	none	18670		
7	**Ru4**	**1a** (4)	708	96	98
8	**Ru4**	**1a** (8)	39	>99	
9	**Ru4**	**9** (4)	11725	37	43
10	**Ru4**	**9** (8)	6456	65	71

[a] Equivalents of scavenger is relative to Ru. [b] Concentration of Ru was calculated as μg Ru per g crude material after solvent evaporation. [c] Determined by ICP-MS. [d] Determined by UV.

Table 3
Ru removal from crude **14**.



13 (DEDMAM) **14**

Entry	RuX	Scavenger[a] (equiv)	[Ru] [ppm][b]	% Removal[c]	% Bound[d]
1	**Ru1**	none	11024		
2	**Ru1**	**1a** (4)	434	96	99
3	**Ru1**	**1a** (8)	36	>99	
4	**Ru1**	**9** (4)	2445	78	40
5	**Ru1**	**9** (8)	1141	90	42
6	**Ru6**	none	9832		
7	**Ru6**	**1a** (4)	45	>99	99
8	**Ru6**	**1a** (8)	28	>99	
9	**Ru6**	**9** (4)	1129	89	3
10	**Ru6**	**9** (8)	580	94	5

[a] Equivalents of scavenger is relative to Ru. [b] Concentration of Ru was calculated as μg Ru per g crude material. [c] Determined by ICP-MS. [d] Determined by UV.

Ru complexes being scavenged may vary between assays (Table 2 and Table 3, entries 2, 3, 7, and 8).

3. Conclusions

New silica-supported aromatic isocyanides were prepared and found to effectively remove Ru from two metathesis reactions using different Grubbs catalysts. By studying a wide variety of Grubbs' metathesis catalysts, the interplay between catalyst structure and aromatic isocyanide structure was comparatively evaluated. During typical grafting conditions, isocyanides were found to undergo partial hydrolysis, so a new method for quantifying isocyanide was developed. With this technique, grafting conditions could be optimized where minimal isocyanide hydrolysis was found. The UV binding assay allowed visualization of reaction rate, optimization of treatment conditions and allowed comparisons of scavenger efficacy. Control reactions with silica gel showed that the Ru complexes examined did not decompose or get removed by silica gel alone. Isocyanides were highly effective at removing Ru precatalysts from solution. Aromatic isocyanide containing materials performed significantly better than commercially-available scavengers and only small differences were found between isocyanide structures. Two RCM reactions were investigated which required drastically different reaction conditions and have high Ru concentrations in the crude organic products. ICP-MS analysis was performed on these products treated with isocyanides followed by a simple filtration. In the RCM examples, 8 equiv of silica-supported isocyanide **1a** can effectively remove Ru to below 40 ppm in all cases and down to 2 ppm in the best example. This was significantly better than commercial scavengers and an improvement from our previous silica-supported alkyl isocyanide which required 60 equiv for comparable Ru removal. The contrasting ability of scavengers to remove Ru in the two RCMs compared to the UV assays using Ru precatalysts alone was attributed to differing degrees of decomposition.

4. Experimental

General. Unless otherwise stated, all reactions were performed using standard Schlenk line technique under nitrogen with oven or flame-dried glassware. Solvents used in reactions were obtained from an anhydrous column purification system. Grubbs carbenes were obtained from Umicore or Materia and used as received. Commercially-available reagents were used as received unless otherwise noted. Triethylamine was distilled before use. Copper(I) chloride was recrystallized from concentrated hydrochloric acid, washed with deionized water and dried in vacuo. Crushed 4 Å molecular sieves were activated and stored at >150 °C in

a drying oven. Flash chromatography was carried out on untreated silica gel 60 from Sorbtech Technologies Inc. (230 – 400 mesh) under air pressure. Thin layer chromatography (TLC) was performed on glass-backed silica plates (F254, 250 micron thickness, EMD Millipore), visualized with UV light, phosphomolybdic acid, iodine, or potassium permanganate. ^{1}H NMR spectra were recorded at 300, 400, or 500 MHz; proton-decoupled ^{13}C NMR spectra were recorded at 75, 100 or 125 MHz using Varian Mercury 300, Inova 400, Inova 500 instruments; proton decoupled ^{1}H NMR chemical shifts are reported in ppm relative to the solvent used (chloroform-d ^{1}H: 7.26 ppm, ^{13}C: 77 ppm, DMSO-d_6 ^{1}H: 2.50, ^{13}C: 39, acetonitrile-d_3 ^{1}H: 1.94, ^{13}C: 118). Infrared spectra were recorded using a Perkin Elmer Spectrum Two FTIR-ATR. Mass analysis was performed on a Bruker SolariX 12T FTMS using electrospray ionization with acetonitrile or dichloromethane as solvent. DRIFT-IR were recorded using a Perkin Elmer Spectrum Two FTIR spectrometer. UV spectroscopy was performed using an Agilent 8453 UV-visible spectrophotometer. UV assays and solutions were performed open to air, stock solutions were prepared in volumetric flasks, and appropriately-sized gas-tight Hamilton syringes were used to transfer measured solutions. All glassware except for disposable pipets used in ICP-MS analyses were pretreated by washing with nitric acid (≥2%) and deionized water, then allowed to dry. Ultrapure water was obtained from a Milli-Q gradient A10 purifier system equipped with a Q-Gard 1 pack and a APS Ultra FP1001 purification pack. In situ infrared spectroscopy was performed with Mettler Toledo ReactIR ic10 and data was acquired in 5 second intervals.

General procedure for cyanogen bromide induced thioether cleavage (using 1a as an example)

A 2 dram vial containing a magnetic stir bar was charged with **1a** (71.6 mg, 17.2 μmol, 1 equiv), activated, crushed, 4 Å molecular sieves (51.0 mg), and acetonitrile-D_3 (0.3 mL), then the mixture was allowed to stir gently at room temperature for 16.2 h. Cyanogen bromide (18.6 mg, 175.6 μmol, 10.2 equiv) dissolved in acetonitrile-d_3 (0.2 mL) was added to the reaction mixture, then the reaction was sealed with a Teflon-lined cap, transferred to a preheated 60 °C oil bath, and allowed to react for 2 h. The reaction was filtered through a glass fiber pipet plug and eluted with acetonitrile-d_3 (0.1 mL four times then 0.2 mL two times). The eluent was allowed to slowly evaporate in the hood over the course of several hours, then the solution was analyzed by ^{1}H NMR by comparing the ratio of isocyanide and formamide cleavage products according to Table S1 (see Supporting Information). It should be noted that evaporating the eluent in vacuo resulted in loss of cleavage products due to their volatility.

General procedure for UV metal binding assays

A 1 dram vial was charged with the measured amount of silica-supported scavenger and a magnetic stir bar. An aliquot of **RuX** in $PhCH_3$ (1000 μL, 2 mM, 2 μmol) was added to the vial and the mixture was stirred at room temperature for 30 min. The time-course analyses were performed at the denoted time intervals. Care was taken such that the stirring was not so rapid that significant amounts of solids deposited out of the solution. The mixture was filtered through a glass fiber pipet plug and eluted with $PhCH_3$ (0.5 mL six times) into a 5 or 10 mL volumetric flask. The volume of eluent was adjusted to the mark with $PhCH_3$, then an appropriate dilution was performed. If the **RuX** used was **Ru1-6**, then the dilution was performed according to **Table S2**. UV spectra were obtained, then the concentration of solution was calculated through the standard curve for **RuX**. Percent bound was calculated as: percent bound = [1-(concentration **RuX** in sample / concentration **RuX** in non-treated sample)] x 100%.

General procedure for in situ FT-IR isocyanide-binding time-course analysis (using 4a and Ru2 as an example)

A stock solution of isocyanide **4a** (232.8 mg, 0.59 mmol, 23.6 mM) in $PhCH_3$ (25.00 mL) was prepared in a 25 mL volumetric flask. A stock solution of Ru carbene **Ru2** (265.1 mg, 0.28 mmol, 56.0 mM) in $PhCH_3$ (5.00 mL) was prepared in a 5 mL volumetric flask. An oven-dried 50 mL ReactIR reaction vessel containing a magnetic stirring bar was cooled to room temperature under the flow of nitrogen. Isocyanide stock solution (3.7 mL, 0.09 mmol, 3 equiv) was added to the reaction vessel and monitored by in situ IR as the temperature and solution equilibrated. If the reaction was performed at 0 °C – as in this example – the reaction was temperature controlled by an ice-water bath, otherwise the temperature was controlled with a recirculating water bath set to 23.5 °C. Ru carbene stock solution (500 μL, 0.03 mmol, 1 equiv) was injected directly into the isocyanide solution, then the reaction was monitored to observe a new stretching frequency corresponding to the Ru-C≡NAr isocyanide stretch at 2103 cm^{-1}.

General procedure for ring-closing metathesis of diethyl diallyl malonate and treatment with silica-supported metal scavengers

All manipulations of stock solutions and metatheses were performed in the glovebox. A stock solution of diethyl diallyl malonate (290 μL, 1.2 mmol) in $PhCH_3$ (3.00 mL) was prepared in a 3 mL volumetric flask. A stock solution of **RuX** (10 μmol) in $PhCH_3$ (5.00 mL) was prepared in a 5 mL volumetric flask. A 20 mL scintillation vial containing a magnetic stir bar was charged with diethyl diallyl malonate stock solution (500 μL, 0.2 mmol, 1.0 equiv), $PhCH_3$ (2.50 mL), and **RuX** stock solution (1000 μL, 0.002 mmol, 0.01 equiv). The reaction was loosely capped and allowed to mix at ambient temperature (29 °C) for 30 min. The vial was sealed, removed from the glovebox, and an appropriate amount of silica-supported metal scavenger was added. The mixture was allowed to stir at ambient temperature for 30 min, then the reaction was filtered through a glass fiber pipet plug and eluted with $PhCH_3$ (0.5 mL six times) into a tared 20 mL scintillation vial. The sample was concentrated in vacuo, dissolved in 0.7 mL $CDCl_3$, and an ^{1}H NMR was taken to determine percent conversion. Percent conversion was calculated from the allylic protons for diethyl diallyl malonate (2.64 ppm, d, ^{3}J = 7.5 Hz, 4 H) and diethyl cyclopent-3-ene-1,1-dicarboxylate (2.99 ppm, s, 4 H). The solution was transferred into the tared vial, rinsing once with CH_2Cl_2 (1.5 mL), then concentrated in vacuo. The mass was recorded, then the crude sample was prepared for ICP-MS analysis.

General procedure for ring-closing metathesis of diethyl di(2-methyl)allyl malonate and treatment with silica-supported metal scavengers

All manipulations of stock solutions and metatheses were performed in the glovebox. A stock solution of diethyl di(2-methyl)allyl malonate (363.6 mg, 1500 μmol) in $PhCH_3$ (3.00 mL) was prepared in a 3 mL volumetric flask. A stock solution of **RuX** (60 μmol) in $PhCH_3$ (10.00 mL) was prepared in a 10 mL volumetric flask. A 1 dram scintillation vial containing a magnetic stir bar was charged with diethyl di(2-methyl)allyl malonate stock solution (250 μL, 125 μmol, 1.0 equiv) and **RuX** stock solution (1000 μL, 6.0 μmol, 0.05 equiv). The reaction was loosely capped and transferred to a preheated 60 °C aluminum block and allowed to react for 24 h. The reaction was sealed, removed from the glovebox, and the appropriate amount of silica-supported metal scav-

enger was added. The mixture stirred for 30 min at rt, was filtered through a glass fiber pipet plug, and washed with $PhCH_3$ (0.5 mL six times) into a tared 20 mL scintillation vial. The solution was concentrated in vacuo, dissolved in 0.7 mL $CDCl_3$, then analyzed by ^{1}H NMR to determine percent conversion. Percent conversion was calculated from the allylic protons for diethyl di(2-methyl)allyl malonate(2.73 ppm, s, 4 H) and diethyl 3,4-dimethylcyclopent-3-ene-1,1-dicarboxylate (2.91 ppm, s, 4 H) . The solution was transferred to the tared scintillation vial, rinsing once with CH_2Cl_2 (1.5 mL), then concentrated in vacuo. The mass was recorded, then the crude sample was prepared for ICP-MS analysis.

Preparation of crude samples for ICP-MS analysis

Once the mass of crude material from metatheses was recorded, nitric acid (1.00 mL, 70%, for trace metals analysis) was added to the 20 mL scintillation vial containing the crude material. The vial was capped with a piece of Kimwipe secured with a rubber band, then the organic material was allowed to digest overnight at room temperature. The nitric acid solution was quantitatively transferred to a 25 mL volumetric flask and diluted to 25.00 mL with ultrapure water. The resulting solution was diluted appropriately, then the sample was filtered through a PTFE syringe filter (25 mm, 0.45 µm membrane) and analyzed by ICP-MS.

Preparation of scavenger materials

N-(4-(Allyloxy)phenyl)formamide (2a)

An oven-dried 250 mL round bottom flask was charged with N-(4-hydroxyphenyl)formamide (7.01 g, 51.1 mmol, 1.0 equiv), oven-dried potassium carbonate (8.16 g, 59.0 mmol, 1.2 equiv), and a magnetic stir bar. The solids were suspended in acetonitrile (45 mL), then the flask was equipped with a reflux condenser. To the stirring solution allyl bromide (5.0 mL, 57.9 mmol, 1.1 equiv) was added dropwise over the course of 15 min and the reaction gradually became yellow. The reaction was transferred to a pre-heated 60 °C oil bath. After 93 h the reaction was cooled to room temperature and a 0.1 mL aliquot was taken for ^{1}H NMR analysis to reveal 68% conversion of N-(4-hydroxyphenyl)formamide to N-(4-(allyloxy)phenyl)formamide had occurred. Additional allyl bromide (2.0 mL, 23.1 mmol, 0.45 equiv) was added dropwise, the reaction was transferred to a preheated 60 °C oil bath, and the reaction turned orange-red upon heating. After 24 h a second 0.1 mL aliquot was analyzed by ^{1}H NMR to show no additional conversion from N-(4-hydroxyphenyl)formamide to N-(4-(allyloxy)phenyl)formamide. The solution was decanted and the solids were subsequently rinsed and decanted three times with CH_2Cl_2, filtered with filter paper, and the filter cake was washed five times with CH_2Cl_2 (25 mL). The filter cake was dissolved in deionized H_2O and extracted three times with CH_2Cl_2. The organic phase was concentrated in vacuo to obtain 8.94 g of a dark red oil. The crude material was purified by flash chromatography (20-100% EtOAc/hexanes) to collect **2a** (5.85 g, 33.0 mmol, 65%) as a light tan solid. Melting point 51-52 °C. R_f 0.45 (70% EtOAc/hexanes), ^{1}H NMR (400 MHz, $CDCl_3$, ppm, minor rotamer reported): δ 8.52 (d, ^3J = 11.6 Hz, 1 H), 8.10 (br s, 1 H), 7.43 (d, ^3J = 9.2 Hz, 2 H), 6.89 (t, ^3J = 9.2 Hz, 2 H), 6.03 (m, 1 H), 5.4 (ddd, ^3J =17.2 Hz, ^3J = 2.0 Hz, ^2J = 2.0 Hz), 5.29 (td, ^3J = 10.0 Hz, ^2J = 1.2 Hz, 1 H), 4.52 (td, ^3J = 4.4 Hz, ^4J = 2.0 Hz, 2 H). $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$, ppm): δ 163.14, 159.01, 156.50, 155.6, 133.07, 132.91, 130.08, 129.70, 121.70, 121.41, 117.84, 117.71, 115.72, 115.05, 69.08, 69.02. FT-IR (ATR, cm^{-1}): 3262, 3129, 3065, 2868, 2075, 1875, 1677, 1601, 1536, 1508, 1456, 1409, 1362, 1291, 1233, 1176, 1150, 1112, 1021, 998, 926, 889, 826, 741, 655, 640, 616, 601, 572, 562, 528. High resolution MS (EI^+, m/z): molecular ion calculated for $C_{10}H_{11}NNaO_2$ [M+Na^+] 200.0682, found 200.0685, error -1.4 ppm.

N-(4-(Allyloxy)-2,6-dimethylphenyl)formamide (2b)

Reaction adapted from the literature [15]. In an oven dried 250 mL round bottom flask a solution of N-(4-hydoxy-2,6-dimethylphenyl)formamide (6.22 g, 37.7 mmol, 1.0 equiv) in DMF (100 mL), potassium carbonate (5.7 g, 41.5 mmol, 1.1 equiv) and allyl bromide (2.55 g, 41.5 mmol, 1.1 equiv) were added. The reaction was monitored by TLC, and upon completion, most of the DMF was removed in vacuo. To the residue was added water (50 mL) and the solution filtered through a Buchner funnel. The remaining light brown crystals were dissolved in CH_2Cl_2 and purified through flash chromatography (50% EtOAc/hexane) to afford product **2b** (2.0 g, 9.74 mmol, 26%) as a white solid. Melting point 144 -146 °C. R_f 0.20 (50% EtOAc/hexanes). ^{1}H NMR (500 MHz, $CDCl_3$, ppm, major rotamer reported): δ 8.38 (s, 1H), 6.71 (br s, 1 H), 6.66 (s, 2 H) 6.03 (m, 1H) 5.38 (dt, ^3J = 17.3 Hz, ^3J = 2.5 Hz, 1 H), 5.28 (td, ^3J = 10.0 Hz, ^3J = 2.5 Hz), 4.49 (d, ^3J = 5.3 Hz, 2 H), 2.26 (s, 6 H) $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$, ppm): δ 165.51, 160.06, 157.52, 137.19, 136.63, 133.24, 133.01, 126.18, 125.48, 117.74, 117.54, 114.47, 114.44, 114.18, 68.79, 18.97, 18.75. FT-IR (ATR, cm^{-1}): 3260, 3087, 2916, 2893, 2865, 1654, 1608, 1593, 1507, 1458, 1424, 1380, 1325, 1281, 1253, 1223, 1172, 1133, 1054, 1005, 964, 931, 883, 852, 736, 700, 652, 618, 579, 527. High resolution MS (EI^+, m/z): molecular ion calculated for $C_{12}H_{15}NO_2$ [M^+] 205.1103, found 205.1101, error -1.3 ppm.

N-(4-(Undec-10-en-1-yloxy)phenyl)formamide (2c)

An oven-dried 250 mL round-bottomed flask with a magnetic stir bar was charged with N-(4-hydroxyphenyl)formamide (1.37 g, 10 mmol, 1.0 equiv), potassium carbonate (2.77 g, 20 mmol, 2.0 equiv), acetonitrile (50 mL), and 11-bromo-1-undecene (3.3 mL, 15 mmol, 1.5 equiv). A reflux condenser was attached and the mixture was gently refluxed at 85 °C for 24 h. The reaction mixture was filtered through celite and concentrated in vacuo. The crude mixture was purified by column chromatography (50% EtOAc/hexanes) to afford the desired product **2c** (5.27 g, 7.50 mmol, 75% yield) as a light-yellow solid. Melting point 66-67 °C. R_f 0.38 (50% EtOAc/hexanes). ^{1}H NMR (400 MHz, $CDCl_3$, ppm, major rotamer reported): δ 8.48 (d, ^3J = 11.5 Hz, 1 H), 7.41 (d, ^3J = 9.0 Hz, 2 H), 7.00 (d, ^3J = 9.0 Hz, 2 H), 5.80 (ddt, ^3J = 17.0 Hz, ^3J = 10.2 Hz, ^3J = 6.7 Hz, 1 H), 4.98 (d, ^3J = 17.0 Hz, 1 H), 4.92 (d, ^3J = 10.2 Hz, 1 H), 3.92 (t, ^3J = 6.6 Hz, 2 H), 2.05-2.0 (m, 2 H), 1.78-1.73 (m, 2 H), 1.44-1.29 (m, 12 H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$, ppm, major rotamer reported): δ 162.8, 158.7, 139.2, 121.8, 115.5, 114.9, 114.1, 66.3, 33.8, 29.5, 29.4, 29.3, 29.2, 29.2, 29.1, 28.9, 26.0. FT-IR (ATR, cm^{-1}): 3112.77, 3078.03, 2920.05, 2850.42, 2753.84, 1742.42, 1643.24, 1515.40, 1472.09, 1248.16. High resolution MS (ESI): m/z calculated for [$C_{18}H_{27}NO_2$+Na]$^+$ 312.1939, found 312.1933, error: -1.9 ppm.

N-(4-(3-((3-Triethoxysilyl)propyl)thio)propoxy)phenyl)formamide (3a)

Reaction was adapted from the literature [5]. An oven-dried 20 mL scintillation vial was charged with **2a** (2.54 g, 14.3 mmol, 1 equiv), 3-mercaptopropyltriethoxysilane (3.45 mL, 14.3 mmol, 1 equiv), Irgacure 651 (54.6 mg, 0.21 mmol, 0.02 equiv), and a magnetic stir bar. The sample was heated gently to promote solvation of Irgacure-651, and then the reaction was cooled to room temperature and irradiated at 365 nm for 3.5 h. The solution became orange and an aliquot was analyzed by ^{1}H NMR to show formamide **3a** (quantitative yield). R_f 0.49 (70% EtOAc/hexanes). ^{1}H NMR (400 MHz, $CDCl_3$, ppm): δ 8.50 (d, ^3J = 11.6 Hz, 0.5 H), 8.33 (s, 0.5 H),

7.43 (d, ^3J = 8.8 Hz, 1 H), 7.01 (d, ^3J = 8.8 Hz, 1 H), 6.87 (app t, ^3J = 9.2 Hz, 2 H), 4.10-3.97 (m, 2 H), 3.81 (q, ^3J = 7.2 Hz, 6 H), 2.68 (td, ^3J = 2.0 Hz, ^3J = 6.8 Hz, 2 H), 2.55 (t, ^3J = 7.6 Hz, 2 H), 2.12-1.97 (m, 2 H), 1.71 (p, ^3J = 8.0 Hz, 2 H), 1.22 (t, ^3J = 7.2 Hz, 9 H), 0.81-0.65 (m, 2 H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$, ppm): δ 163.10, 159.12, 156.60, 155.69, 130.09, 129.61, 121.56, 121.17, 115.28, 114.70, 114.59, 66.42, 66.36, 58.20, 34.92, 29.12, 29.04, 28.14, 28.10, 22.96, 18.28, 18.09, 9.65, 9.63. FT-IR (ATR, cm^{-1}): 2974, 2926, 1682, 1603, 1511, 1471, 1413, 1391, 1294, 1236, 1166, 1100, 1073, 957, 913, 828, 779, 730, 646, 528, 479. High resolution MS (EI^+, m/z): molecular ion calculated for $C_{19}H_{34}NO_5SSi$ [M^+] 416.1921, found 416.1922, error -0.2 ppm.

N-(2,6-Dimethyl-4-(3-((3-(triethoxysilyl)propyl) thio)propoxy)phenyl)formamide (3b)

To a stirred solution of **2b** (0.765 g, 5.35 mmol, 1.0 equiv) and $CDCl_3$ (1.5 mL) in a one-dram vial was added 3-mercaptopropyltriethoxysilane (1.37 mL, 5.35 mmol, 1.0 equiv) and Irgacure 651 (27.4 mg, 0.107 mmol, 0.02 equiv). The solution was flushed with argon then irradiated at 365 nm for 24 h. The crude solution was purified through flash chromatography (50% EtOAc/hexanes) to afford product **3b** (1.0 g, 2.3 mmol, 50% yield) as yellow oil. R_f 0.20 (50% EtOAc/hexanes). ^1H NMR (300 MHz, $CDCl_3$, ppm, major rotamer reported): δ 8.39 (s, 1 H), 6.81 (br s, 1 H), 6.64 (s, 2 H), 4.02 (t, ^3J = 6.0 Hz, 2 H), 3.82 (q, ^3J = 7.0 Hz, 6 H), 2.68 (t, ^3J = 7.0 Hz, 2 H), 2.55 (t, ^3J = 7.1 Hz, 2 H), 2.24 (s, 6 H), 2.03 (p, ^3J = 7.0 Hz, 2 H), 1.73 (p, ^3J = 7.5 Hz, 2 H), 1.24 (t, ^3J = 7.0 Hz, 9 H), 0.75 (t, ^3J = 8.0 Hz, 2 H). $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$, ppm): δ 165.43, 159.95, 157.85, 137.22, 136.65, 126.00, 125.31, 114.19, 113.98, 66.27, 58.38, 35.14, 29.29, 28.36, 23.17, 18.96, 18.75, 18.29, 9.87. FT-IR (ATR, cm^{-1}): 3244, 2972, 2923, 2882, 1666, 1596, 1488, 1439, 1387, 1326, 1277, 1249, 1167, 1100, 1074, 958, 852, 834, 780, 701, 629. High resolution MS (EI^+, m/z): molecular ion calculated for $C_{21}H_{37}NNaO_5SSi$ [M^+Na^+] 466.2059, found 466.2053, error -0.1 ppm.

N-(4-((11-((3-(Triethoxysilyl)propyl)thio)undecyl)oxy)phenyl) formamide (3c)

To an oven-dried 20-mL scintillation vial with a magnetic stir bar was charged with **2c** (2.17 g, 7.5 mmol, 1.0 equiv), 3-mercaptopropyltriethoxysilane (1.81 mL, 7.5 mmol, 1.0 equiv), and Irgacure 651 (38.4 mg, 0.15 mmol, 0.02 equiv). To dissolve the solid, chloroform (3 mL, purified by passing through a short alumina column before use) was added. The solution was irradiated at 365 nm for 24 h then concentrated in vacuo. The crude product was purified by column chromatography (25% EtOAc/hexanes) to afford **3c** (3.7 g, 7.12 mmol, 95% yield) as a brown oil. R_f 0.15 (25% EtOAc/hexanes). ^1H NMR (400 MHz, $CDCl_3$, ppm, major rotamer reported): δ 8.49 (d, ^3J = 11.6 Hz, 1 H), 7.42 (d, ^3J = 8.9 Hz, 2 H), 7.01 (d, ^3J = 8.9 Hz, 2 H), 3.93 (t, ^3J = 6.4 Hz, 2 H), 3.81 (q, ^3J = 7.0 Hz, 6 H), 2.53 (t, ^3J = 7.5 Hz, 2 H), 2.49 (t, ^3J = 7.5 Hz, 2 H), 1.75-1.59 (m, 4 H), 1.57-1.46 (m, 2 H), 1.38-1.23 (m, 14 H), 1.22 (t, ^3J = 7.0 Hz, 9 H), 0.76-0.72 (m, 2 H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$, ppm, major rotamer reported): δ 162.9, 158.7, 141.3, 121.8, 115.5, 68.4, 58.4, 35.2, 32.0, 29.8, 29.5, 29.5, 29.3, 29.2, 29.2, 29.2, 28.9, 26.0, 23.2, 18.3, 9.9. FT-IR (ATR, cm^{-1}): 3112, 3077, 2919, 2850, 2754, 1746, 1516, 1473, 1249. High resolution MS (ESI): m/z calculated for $[C_{27}H_{49}NO_5SSi+Na]^+$ 550.2998, found 550.2998, error: 0 ppm.

Triethoxy(3-((3-(4-isocyanophenoxy)propyl)thio)propyl)silane (4a)

Reaction was adapted from the literature [1a]. In an oven-dried 50 mL round bottom flask **3a** (4.46 g, 10.7 mmol, 1 equiv) and triethylamine (7.5 mL, 54 mmol, 5.0 equiv) were dissolved in THF (13.4 mL) then cooled to -78 °C via dry ice/acetone. A solution of phosphorus(V) oxychloride (1.22 mL, 13 mmol, 1.2 equiv) in THF (5.6 mL) was added dropwise to the stirring formamide-containing solution. The reaction was allowed to mix at -78 °C for 5 min, then the flask was transferred to a 0 °C ice-water bath and allowed to react for 2 h. The reaction was stored at -20 °C in a freezer overnight. The reaction was warmed to 0 °C, then ice cold deionized water (13 mL) was added slowly. The reaction was extracted four times with Et_2O, washed once with brine, then dried over sodium sulfate. The crude product was concentrated in vacuo, then purified by column chromatography (5-20% EtOAc/hexanes) to obtain **5a** (2.94 g, 7.4 mmol, 69% yield) as a colorless oil with a disagreeable odor. R_f 0.24 (10% EtOAc/hexanes). ^1H NMR (300 MHz, $CDCl_3$, ppm): δ 7.30 (d, ^3J = 9.0 Hz, 2 H), 6.86 (d, ^3J = 9.0 Hz, 2 H), 4.06 (t, ^3J = 6.3 Hz, 2 H), 3.82 (q, ^3J = 6.9 Hz, 6 H), 2.71 (t, ^3J = 6.9 Hz, 2 H), 2.55 (t, ^3J = 7.5 Hz, 2 H), 2.06 (p, ^3J = 6.9 Hz, 2 H), 1.71 (p, ^3J = 7.2 Hz, 2 H), 1.22 (t, ^3J = 6.9 Hz, 9 H), 0.78-0.68 (m, 2 H). $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$, ppm): δ 156.47, 58.06, 57.95, 39.94, 39.85, 39.78, 38.23, 34.71, 33.53, 28.62, 27.98, 23.15, 22.90, 22.32, 18.45, 18.00, 9.51. FT-IR (ATR, cm^{-1}): 2973, 2925, 2883, 2122, 1606, 1584, 1505, 1468, 1440, 1389, 1297, 1250, 1193, 1164, 1100, 1075, 1029, 958, 833, 781, 523. High resolution MS (EI^+, m/z): molecular ion calculated for $C_{19}H_{31}NNaO_4SSi$ [$M+Na^+$] 420.1635, found 420.1645, error -2.4 ppm.

Triethoxy(3-((3-(4-isocyano-3,5-dimethylphenoxy)propyl) thio)propyl)silane (4b)

Reaction was adapted from the literature. [1a] To an oven-dried 5 mL round bottom flask **3b** (379 mg, 0.85 mmol, 1.0 equiv) and triethylamine (0.595 mL, 4.27 mmol, 5.0 equiv) were added to THF (1.0 mL) and cooled to -78 °C. A solution of $POCl_3$ (0.096 mL, 1.03 mmol, 1.2 equiv) in THF (0.500 mL) was added dropwise to the formamide solution. After 1 h the reaction was placed in an ice bath and allowed to stir for 1 h then the solution was quenched with ice-water (3.0 mL). The reaction was then extracted with diethyl ether (three time with 3.0 mL) and the organic layer dried over Na_2SO_4. The reaction was concentrated in vacuo to afford crude yellow oil, which was purified through a silica pipette (20% Et_2O/hexanes) to give product **4b** (0.118 g, 2.78 mmol, 33% yield) as a yellow oil. R_f 0.30 (20% Et_2O/hexanes). ^1H NMR (300 MHz, $CDCl_3$, ppm): δ 6.59 (s, 2 H), 4.03 (t, ^3J = 6.1 Hz, 2 H), 3.81 (q, ^3J = 7.0 Hz, 6 H), 2.67 (t, ^3J = 7.1 Hz, 2 H), 2.55 (t, ^3J = 7.2 Hz, 2 H), 2.38 (s, 6 H), 2.03 (p, ^3J = 6.6 Hz, 2 H), 1.71 (p, ^3J = 8.0 Hz, 2 H), 1.22 (t, ^3J = 7.0 Hz, 9 H), 0.73 (t, ^3J = 8.0 Hz, 2 H). $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$, ppm): δ 158.45, 136.43, 113.51, 66.37, 58.37, 35.15, 29.10, 28.26, 23.17, 22.61, 19.14, 18.28, 9.89, 9.43 FT-IR (ATR, cm^{-1}): 2973, 2925, 2884, 2113, 1605, 1594, 1481, 1466, 1441, 1389, 1329, 1292, 1249, 1192, 1154, 1141, 1100, 1075, 997, 958, 914, 858, 838, 781, 733, 713, 647, 629, 557. High resolution MS (EI^+, m/z): molecular ion calculated for $C_{21}H_{35}NNaO_4SSi$ [M^+Na^+] 448.1954, found 448.1948, error -1.0 ppm

Triethoxy(3-((11-(4-isocyanophenoxy)undecyl)thio)propyl)silane (4c)

An oven-dried round-bottomed flask with a magnetic stir bar was charged with formamide **3c** (1.06 g, 2 mmol, 1.0 equiv), triethylamine (1.4 mL, 10 mmol, 5 equiv) and THF (20 mL). The reaction was cooled to -78 °C by dry ice/acetone bath. Phosphorous oxychloride (0.22 mL, 2.4 mmol, 1.2 equiv) dissolved into THF (12 mL), was then slowly added to the reaction flask. The dry ice/acetone bath was replaced by an ice-water bath to warm the reaction flask to 0 °C. After 2 hours at 0 °C, water (10 mL) was added slowly to quench the reaction. The mixture was then extracted with Et_2O (three times with 10 mL), washed with brine

(three times with 10 mL), and dried over Na_2SO_4. Solvent was removed in vacuo, and the crude product was purified by column chromatography (25% EtOAc/hexanes with 1% Et_3N) to give **4c** (610 mg, 1.20 mmol, 60% yield) as a light yellow oil. R_f 0.45 (25% EtOAc/hexanes). ^1H NMR (300 MHz, $CDCl_3$, ppm): δ 7.21 (d, ^3J = 7.5 Hz, 2 H), 6.84 (d, ^3J = 7.5 Hz, 2 H), 6.78 (t, ^3J = 6.6 Hz, 2 H), 3.88 (q, ^3J = 7.2 Hz, 6 H), 2.47 (t, ^3J = 7.5 Hz, 2 H), 2.43 (t, ^3J = 7.5 Hz, 2 H), 1.75-1.59 (m, 4 H), 1.57-1.46 (m, 2 H), 1.38-1.23 (m, 14 H), 1.17 (t, ^3J = 7.2 Hz, 9 H). 0.71-0.66 (m, 2 H). $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$, ppm): δ 162.7, 159.4, 139.0, 127.6, 115.0, 114.1, 68.3, 58.3, 35.1, 33.7, 31.9, 29.7, 29.4, 29.3, 29.3, 29.2, 29.0, 28.9, 25.9, 23.2, 18.3, 9.8. FT-IR (ATR, cm^{-1}): 2973, 2924, 2894, 2121, 1606, 1504, 1251, 1076.12; High resolution MS (ESI): m/z calculated for $[C_{27}H_{47}NO_4SSi+Na]^+$ 532.2893, found 532.2903, error: 1.9 ppm.

Silica-bound triethoxy(3-((3-(4-isocyanophenoxy)thio)propyl)silane (1a)

An oven-dried 50 mL round-bottom flask containing a magnetic stir bar was charged with silica gel (3.23 g, F60, 40-63 μm, 60 Å), PhH (9.0 mL), and triethylamine (0.6 mL, 4.3 mmol, 0.7 equiv). Isocyanide **4a** (2.39 g, 6.03 mmol, 1.0 equiv.) was dissolved in PhH (1.5 mL) and added slowly to the stirring suspension. The reaction was allowed to mix at room temperature for 17 h. The solids were collected by filtration on a medium porosity sintered glass funnel and washed with anhydrous Et_2O four times then anhydrous CH_2Cl_2 four times. The solids were allowed to dry under vacuum. The eluent was concentrated in vacuo to recover isocyanide **4a** (1.98 g, 5.0 mmol, 83% recovery). A 50 mg aliquot of the solid was taken, shaken with 0.7 mL $CDCl_3$, filtered, and the eluent was analyzed by ^1H NMR to verify that no residual triethylamine was present. Solids were transferred to a vacuum oven and dried at 40 °C, 25 in Hg for 6 h. Silica-bound scavenger **1a** (3.284 g) was collected as an off-white powder. Elemental analysis: (%N = 0.34; 0.24 mmol/g N). FT-IR (DRIFT IR, KBr, cm^{-1}) 2151, 2125.

Silica bound triethoxy(3-((3-(4-isocyano-3,5-dimethylphenoxy) propyl)thio)propyl)silane (1b)

To a suspension of silica (1.17 g, F60, 40-63 μm, 60 Å) and PhH (3.84 mL) was added isocyanide **4b** (0.935 g, 2.19 mmol, 1.0 equiv) and triethylamine (0.214 mL, 1.53 mmol, 0.7 equiv). The reaction was stirred for 20 h at room temperature. The solids were collected by filtration on a medium porosity sintered glass funnel and washed with anhydrous Et_2O four times then anhydrous CH_2Cl_2 four times. The solids were dried under vaccuum and the eluent was concentrated in vacuo to recover **4b** (0.407 g, 0.956 mmol, 44% recovery). A 50 mg aliquot of the solid was shaken with 0.7 mL $CDCl_3$, filtered, and the eluent analyzed by ^1H NMR to verify no residual triethylamine was present. The solids were transfered to a vaccuum oven and dried at 40 °C, 25 in Hg for 6 h. Silica bound scavenger **2b** (1.20 g) was collected as an off white powder. Elemental analysis: (%N = 0.22; 0.18 mmol/g N). FT-IR (DRIFT IR, KBr, cm^{-1}) 2117, 2140.

Silica-bound triethoxy(3-((11-(4-isocyanophenoxy)undecyl)thio) propyl)silane (1c)

In an oven-dried 25 mL round-bottomed flask containing a stir bar, silica gel (640 mg, F60, 40-63μ μm, 60 Å), PhH (5 mL), triethylamine (0.12 mL, 0.85 mmol, 0.7 equiv) and **4c** (610 mg, 1.2 mmol, 1.0 equiv) were mixed for 24 h at room temperature. The mixture was filtered, and the solids collected from filtration were washed with anhydrous THF (three times with 10 mL) followed by anhydrous diethyl ether (three times with 10 mL). Isocyanide **4c** (439 mg, 0.87 mmol, 73% recovery) was recovered by concentrating the combined filtrate in vacuo. The solids were dried in vacuum oven at 50 °C for 24 h to give silica-bound scavenger **1c** (690 mg). Elemental analysis: (%N = 0.38; 0.27 mmol/g N). FT-IR (DRIFT IR, KBr, cm^{-1}) 2149, 2125.

Silica-bound N-(4-(3-((3-triethoxysilyl)propyl)thio)propoxy)phenyl) formamide (5a)

An oven dried 25 mL round-bottom flask was charged with silica gel (1.01 g, F60 40-63 μm, 60 Å), PhH (3.4 mL), and triethylamine (0.19 mL, 0.03 mmol, 0.02 equiv). Formamide **3a** (778.4 mg, 1.87 mmol, 1.0 equiv) was added and the reaction was allowed to mix at room temperature for 18 h. Solids were filtered through a medium porosity fritted glass funnel then washed with anhydrous Et_2O (approx. 75 mL) then anhydrous CH_2Cl_2 (approx. 75 mL). The solids were dried under vacuum, then dried at 40 °C, 25 in Hg for 11.5 h. Silica bound formamide **5a** (1.09 g) was collected as a white powder. Elemental analysis: (%N = 0.36; 0.26 mmol/g N). FT-IR (DRIFT IR, KBr, cm^{-1}) 1678.

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Declaration of Competing Interest

One of the authors (S.T.D.) has filed a provisional patent with the University at Buffalo using isocyanides for the removal of metals from reactions.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jorganchem.2021.121800.

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[10] Isocyanide 4c was not investigated since the steric variation of 1c is due to the distance of the isocyanide to the silica surface which is not present in solution phase experiments.
[11] It should be noted that although isocyanide binding of Ru2 may not have reached completion within 30 min, all other Ru carbenes show >90% conversion after this time period using 4 equiv 1a-1c. This suggests that these Ru carbenes may have similar binding rates to Ru1.
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