SYNTHESIS OF STRUCTURED SILOXANE ARCHITECTURES

METHODS FOR CONTROL IN THE SYNTHESIS OF STRUCTURED SILOXANE ARCHITECTURES

By

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Abstract

The advantageous properties of siloxanes find use in a wide range of applications. Unfortunately, the dynamic nature of silicones which is responsible for these properties is often a limitation in the controlled synthesis and modification of siloxane materials. Gaining greater control over these processes would allow for the synthesis of siloxane materials with more explicit structures, giving them a narrower range of properties and expanding application. Furthermore, the ability to synthesize more siloxane architectures with greater control would allow for an increased understanding of the relationship between structural features and physical properties.

The synthesis of hydrosilane-rich siloxane elastomers and subsequent controlled modification, particularly with poly(ethylene oxide), is described. The effect of chain length and functionality (mono- or di-) was found to influence the morphology of grafted polymer. It was also possible to take advantage of the intrinsic properties of siloxanes to sequester hydrophilic moieties to the interior of the elastomer. Utilizing the same hydrosilane rich elastomers, a method for the independent modification of the interior and exterior of hydrosilane rich elastomers is presented. The careful selection of grafting moieties and solvents is used to provide or deny transport to the interior of the elastomer. This method is used to synthesize PEO modified elastomers with various subsequent internal modifications.

A method for controlled synthesis of silicone-carbohydrate composites is also described. Utilizing bifunctional silane linkers, protected carbohydrates were functionalized with bulky diisopropyl hydrosilane groups before linkage to short and long silicones. Alternatively, the linker could first be joined to a silicone, followed by silylation of unprotected saccharides using the resultant hindered chlorosilane functional silicone. This method gave preferential silylation at primary hydroxyl groups.

Finally, a method is presented for the synthesis of explicit branched siloxane architectures. The $B(C_6F_5)_3$ catalyzed dehydrocarbonative coupling of hydrosilanes with alkoxysilanes was used to construct branched siloxane architectures in a stepwise fashion. High levels of control were available through manipulation of steric parameters: careful selection of starting materials and conditions allowed for the synthesis of explicit alkoxysilane functional branched siloxanes. These could be grafted to hydrosilane functional silicone polymers, or used to assemble explicit branched siloxanes. Further explorations demonstrated that the assembly process was not inhibited by the presence of organohalide- or alkene functional groups, allowing for the synthesis of functional siloxane moieties with explicit structures.

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1.1 Silicones

1.1.1 Background

Silicone chemistry is a field with a relatively short history. Although pioneering work was undertaken by Kipping at the turn of the 20th century, it was not until the 1940's that silicone chemistry gained prominence with the advent of the Direct Process.[1-3] Despite this short history, silicones have found extraordinarily broad application. In his 1954 book *Silicones and Their Uses,* McGregor devotes 20 pages to the applications of siloxanes, just a decade after they became widely available.[4] Much broader application is provided in Noll's seminal treatise a decade later.[5] This wide use is primarily a consequence of the unique properties of siloxanes, which cannot be matched by their hydrocarbon equivalents. In the preface to Clarson's comprehensive book on the chemistry and applications of siloxane polymers, Rochow reflects that the properties of silicones "were so different from those of the established materials that the silicone polymers were bound to find a place just because they could do some things the ordinary polymers could not do".[6] While still comparatively expensive by the standards of organic materials, silicones now comprise a global multi billion dollar industry[1] and innovative manipulation of siloxane systems continues to expand their application.

Silicones are polymers consisting of an alternating silicon-oxygen (siloxane) backbone, featuring organic groups at silicon. At the time of their discovery siloxanes, having the general formula R_2SiO, were believed to be the silicon analogues of ketones. In keeping with organosilicon nomenclature (CH_4 = methane; SiH_4 = silane) Kipping coined the term silicone to describe compounds he believed featured a silicon-oxygen π-bond.[1, 7] While compounds featuring this structural motif have thus far proven impossible to isolate,[8] the term silicone has persisted as a general name by which to refer to siloxane materials. The great majority of silicone polymers feature two methyl groups at silicon, and are referred to as polydimethylsiloxane or PDMS (Figure 1.1). Silicones are hybrid polymers, featuring both organic (R groups at silicon) and inorganic (siloxane backbone) structural elements. As discussed below, the behaviour resulting from the combination of these disparate features is responsible for the desirable, and unusual, properties of silicones.

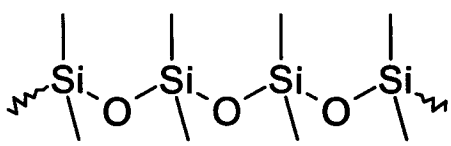


Figure 1.1: Structure of dimethylsilicone

1.1.2 Properties of PDMS

The properties of siloxane polymers are generally discussed by comparison to organic polymers such as polyethylene. By these standards, silicones exhibit high thermal stability (which typically exceeds 350 °C), oxygen permeability, electrical resistance, low surface energy and biocompatibility. For in depth discussions on the use of siloxane materials in various applications and how they relate to the properties and structure of silicones, please see references 1, 9 and 10.

It is generally accepted that many of the properties of siloxanes are a consequence of the dynamic nature of the siloxane backbone.[9] The energy barrier for rotation about siloxane bonds in PDMS is essentially zero, compared with 14 kJ/mol for C-C bond rotation in polyethylene.[9] Moreover, the very large Si-O-Si bond angle (*ca.*145°) and low bending force constant associated with this linkage results in an exceptionally flexible polymer.[11] This is reflected in the glass transition temperatures for methyl siloxanes, which are typically below 120 °C.[1, 9] The extreme flexibility of the siloxane backbone contributes not only to the fluidity of silicones but also to their hydrophobicity and low surface energy: the polymer rearranges to present methyl groups at air interfaces.

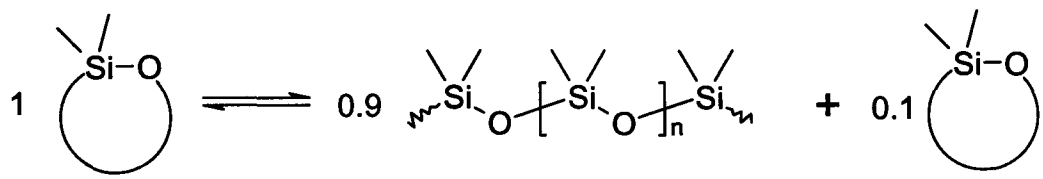
1.1.3 Silicone Synthesis

The root starting material for PDMS based materials is normally dichlorodimethylsilane, although direct hydrolysis generally does not lead to acceptable yields of linear, high molecular weight polymer. It is more common to

use hydrolysis of this, or derivatives such as diethoxydimethylsilane, for the preparation of low molecular weight cyclic silicone oligomers such as D_3, D_4 and D_5, (for an explanation of siloxane nomenclature, please see ref 12) as it is possible to do so in very high yields.[1, 5] These cyclic starting materials can then be used to synthesize silicone polymers by ring opening polymerization by two general methods: thermodynamic ring opening polymerizations using acid or base catalysis, or living anionic ring opening polymerization.[13]

Polysiloxanes exist in equilibrium between cyclic (ring) and linear (chain) forms (Scheme 1.1).[1, 14, 15] While this ring/chain equilibrium is sufficiently slow to be ignored under neutral conditions, it can be accelerated for synthetic purposes through the use of acid or base catalysis.[16] Essentially, the lability of siloxane bonds in the presence of acid or base leads to the establishment of an equilibrium under thermodynamic control, under which conditions the concentration of cyclic oligomers remains constant. As a practical matter, this means that the combination of end groups, cyclic oligomers and an initiator will lead to the formation of a ring/chain equilibrium. Any dilution of the reaction mixture favours small rings at the expense of higher polymer. As a consequence, performing these polymerizations in the absence of solvent maximizes the concentration of high molecular weight linear polymers.[5] Dilution can also be provided by increased size of the organic groups on silicon: while dimethylsilicones have an equilibrium concentration of about 15% D_4, $F_3CCH_2CH_2$,Me silicones contain about 85% cyclics at equilibrium. Synthetically,

once equilibrium has been achieved, the catalyst must be quenched, and low Mw rings should be removed *in vacuo* to give a finished product. This equilibrium based redistribution process is effective for large scale synthesis of polymers.



Scheme 1.1: Siloxane ring/chain equilibrium

It is possible to gain somewhat greater control over the synthesis of silicone polymers through kinetic control. Under the proper conditions, living anionic ring opening polymerization of cyclic siloxane oligomers can allow for the synthesis of high molecular weight polymers with low PDI.[13, 17] In the presence of an anionic initiator (such as trimethylsilanolate[17, 18] or butyllithium[19]), nucleophilic attack at silicon ring opens cyclic siloxanes, incorporating the initiator at one terminus and creating a silanolate anion at the other. This process repeats, growing the chain until most or all of the remaining cyclics are consumed, or until the process is terminated by an end capping agent. This process works best utilizing strained cyclics, of which only hexamethylcyclotrisiloxane is widely available.

Kinetic polymerizations of silicones suffer from a number of practical complications. Water and other contaminants must be rigorously excluded from the reaction to prevent unintended termination of the living silanolate.

Additionally, due to the reactive nature of the silicone backbone, the living silanolate anion can "back-bite" its own polymer chain, truncating the chain and leading to the production of cyclic species. This process shifts control from kinetic to thermodynamic, with corresponding shifts to lower molecular weight, higher PDI polymers.[1, 16]

Despite their apparent drawbacks, these methods comprise the main methods for silicone synthesis. Silicone polymers have not undergone the same evolution in synthetic control observed for hydrocarbon polymers.[20, 21] Essentially, the reactivity exploited for the polymerization of silicones self limits the amount of synthetic control available. Because of this, controlled assembly of more complicated siloxane architectures (branched polymers, dendrimeric systems etc) are virtually unknown in silicone chemistry. Attempts to synthesize such structures using acid and base catalysis would simply result in the establishment of an equilibrium, removing most elements of synthetic control.

Silicone structures featuring branched siloxanes, such as MQ resins, are known, and their properties make them extremely valued, particularly for interfacial control in complex silicone formulations.[22] These resins are generally synthesized through the relatively uncontrolled hydrolysis of silane precursors, and as such are mixtures of random structures. The ability to synthesize more explicit structures would not only result in materials with a narrower range of properties, but also allow for a better understanding of the relationship between structural features and physical properties.

1.1.4 Functional Silicones

A large proportion of silicone polymers are prepared with additional functional groups to allow further modification that can be arrayed along the silane backbone, or at either or both termini of the polymer (Figure 1.2). Common functional groups found in commercial siloxane polymers include amines, alkenes, hydrosilanes and haloalkanes.[23] These groups are frequently utilized to introduce moieties to modify the properties of siloxanes such as the addition of hydrophilic groups to alter surface properties, such as polyethers in silicone surfactants.[24] It is important to note that the reactive nature of the siloxanes themselves is often the limiting factor in utilization of functional groups. Reactions requiring acidic or basic conditions, as well as certain strong nucleophiles and electrophiles, can degrade the polymer backbone, rather than perform the desired transformation (see section 1.4). Because functional silicones (such as vinyl terminated PDMS) are generally synthesized using the same methods discussed for non-functional polymers, they suffer from the same lack of control in synthesis. This means that the behaviour of commercially important modified silicone species (surfactants, super wetters, foam control agents, etc.) prepared from these functional polymers is largely dependent on the averaged properties of highly polydisperse, inexplicit silicone fragments.

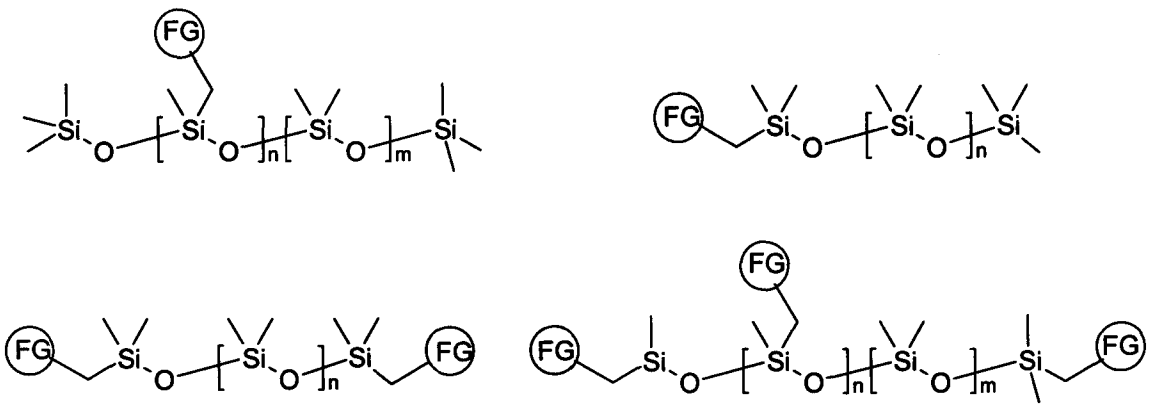


Figure 1.2: Common structural motifs for functional polysiloxanes

1.1.5 Crosslinking of Silicones

One of the most prevalent uses of functional siloxanes is for the synthesis of silicone elastomers.[25] Many applications for which the properties of silicones are beneficial require non-liquid materials, and range from waterproof silicone seals and gaskets to medical prostheses.[26] By utilizing functional groups to create covalent bonds between multiple siloxane chains, it is possible to crosslink silicones to form siloxane elastomers. These elastomers retain many of the properties of siloxane fluids, as the linear siloxane chains, such as thermal stability, low toxicity and hydrophobicity. It is possible to control the physical properties of elastomers of this type by controlling the crosslink density, and by adding fillers (to increase rigidity) or swelling agents (to decrease rigidity). This allows the synthesis of siloxane 'solids' that range from gels to brittle glasses.

There are three primary methods used to 'cure' functional siloxanes into elastomers. High temperature vulcanization (HTV) involves the radical

crosslinking of siloxane elastomers . Thermal homolylsis of radical initiators such as benzoyl peroxide or *t*-butyl peroxide are used to create radicals, either at methyl for non-functional siloxanes[27] or at vinyl functional siloxanes.[28] Radical coupling processes result in covalent crosslinks. While effective for bulk crosslinking of industrial materials, this method lacks the ability to control where crosslinks take place, and typically exhibits poor functional group compatibility. For these reasons, HTV is generally not employed for applications where greater control is desired.

In Room Temperature Vulcanization (RTV), siloxane chains are crosslinked using nucleophilic substitution. Generally speaking, this method involves silanol-terminated PDMS reacting with tri- or tetra-functional silane electrophiles.[1, 29] These nucleophilic substitution reactions can be uncatalyzed, as with acetoxy-functional silanes, though more frequently involve organo-tin or –titanium catalyzed reactions with less reactive alkoxysilane leaving groups, as is the case with tetraethoxysilane (TEOS).[30] Control is somewhat improved over HTV: crosslinks are found only at the termini of the linear polymers, and crosslink density can be controlled by the ratio of the electrophilic crosslinker. Unlike other methods, RTV crosslinking allows the construction of 'pure' silicones: all crosslinks, as well as the polymer backbones, consist of siloxane linkages. Non-functional elastomers of this type do not lend themselves to subsequent modification to create higher value materials. However, some success has been achieved utilizing co-cure strategy employing alkoxysilyl functional copolymers.[31]

Addition cure is a widely employed technique for the crosslinking of siloxane elastomers. This involves the hydrosilylation of vinyl or allyl functional siloxanes with hydrosiloxanes in the presence of a platinum catalyst (see section 1.3.3). The robust nature of this reaction, as well as the high degree of control over the properties of the resultant elastomer, make this the method of choice for silicones in biomedical applications.[29, 32] Elastomers of this type are frequently prepared from commercially available two part kits: one part containing hydrosiloxanes, the other containing (most often) vinyl functional silicones and platinum catalyst. The product elastomers are widely employed starting materials for a number of silicone applications. Moreover, the tractable nature of the hydrosilylation reaction may provide interesting opportunities in the synthesis of functional elastomers.

1.2 Synthetic Control in Silicone Materials

1.2.1 Motivations for Increased Control

As has been discussed briefly in the previous section, control of siloxane polymers is an ongoing synthetic challenge due to their dynamic and reactive nature in the presence of acids or bases. It is the opinion of the author, however, that overcoming these challenges is justified by the potential benefits of improved materials. The ability to direct the explicit synthesis of siloxane fluids, resins and elastomers would give them narrower range of structural features, leading

consequently to a narrower range of properties. This would not only increase the value of the many silicone based products available, but would allow for a greater understanding of how explicit structural features in silicones affect their properties and behaviour.

1.2.2 Attempts at Control in Synthesis of Silicone Fluids

There have been a number of attempts to gain increased control over the synthesis of siloxane fluids in order to obtain more explicit structures. One area of exploration has been in the use of cyclic siloxanes with mixed substituents such as aryl groups. Early reports have claimed high levels of synthetic control from the ring-opening polymerization of such systems, with interesting resulting properties.[33] More recent research has demonstrated that the polymers derived from such mixed oligomers under both anionic[34] and cationic[35] conditions arise from a number of complex and competing processes, which lead to a number of potential microstructures in the resulting polymer. That is, partial control is provided by the use of well-defined precursors. As with any siloxane synthesis utilizing cyclic oligomers, unless carefully monitored these reactions can fall prey to equilibration processes, which would destroy any control of polymer structure.

Attempts have also been made to gain control over silicones prepared via condensation processes. The reaction of silanol (Si-OH) functional groups with chlorosilanes results in the formation of a siloxane bond. By utilizing hydrosilane groups as silanol precursors, Masamune and coworkers developed an iterative

process for the formation of siloxane bonds.[36] This method was reportedly utilized to produce linear siloxanes with perfect polydispersity, as well as a silicone dendrimer. Unfortunately, competing self condensation of silanols, as well as the volatile and highly reactive nature of the hydrosilanes utilized, makes this method impractical, particularly for large scale processes.

Perfectly alternating siloxane co-polymers can reportedly be prepared via an interfacial reaction between dimethyl or diphenyl-silane diolates with dichlorodiorganosilanes.[37] While this process may prove effective for the synthesis of short polymers, condensation polymerizations of silicones do not produce high molecular weight materials, and the reaction seems likely to suffer from problematic side reactions and self-condensations. To date, an in-depth examination of these materials and their properties resulting from this procedure have not yet been reported.

1.2.3 Control in Modification of Silicone Elastomers

Some properties of silicones, such as low toxicity, oxygen permeability and transparency make them attractive in biological applications. Silicones are frequently employed as implantable materials, both for cosmetic purposes (such as silicone breast implants), or to fulfil a medical purpose, such as silicone shunts[38] and stents.[39] It is often the case, however, that the hydrophobicity of silicones can complicate their use in certain applications. For example, while the transparency of silicones makes them attractive in ocular applications,

hydrophobic silicones suffer from protein fouling, that can render them opaque.[40] Protein denaturation can also be problematic. In such instances, it is common to surface modify silicones through covalent grafting of hydrophilic moieties[31, 40-42] While reactions such as acid catalyzed incorporation of poly(hydro methyl)siloxane have been utilized to functionalize the surfaces, these reactions suffer from lack of reproducibility, and it is difficult to achieve high degrees of functionality without negatively affecting the physical properties of the elastomer. For example, in the grafting step (via hydrosilylation, see section 1.3), these reactions suffer from problems such as low graft density, and poor control of morphology for grafted polymer.

Silicone elastomers have also been proposed as methods to deliver drugs[43, 44] enzymes,[45] and to encapsulate and control catalytic species.[46, 47] However, the inability to simultaneously control the surface properties of these elastomers limits their practical application. For example, with respect to immobilized catalysts, it is necessary for hydrophobic compounds to diffuse across the silicone membrane to undergo reaction.[46] While hydrophobic compounds will normally cross silicone boundaries to some degree, hydrophilic compounds would be far less likely to reach the encapsulated material, particularly in the aqueous systems described. There is, therefore, interest in learning how to control the external and internal chemical properties and morphology to optimize silicone performance.

1.3 Hydrosilanes

1.3.1 General

The activation of carbon hydrogen bonds for synthetic purposes remains an ongoing challenge in organic chemistry.[48, 49] In contrast to this, the activation and reaction of silicon hydrogen (hydrosilane) bonds is well understood and frequently employed.[50, 51] The change in reactivity in going from carbon to silicon can be attributed to two main factors. The increased size of silicon leads to poor orbital overlap with hydrogen. This can be seen in longer Si-H bond lengths, reflecting the weaker bond strength compared to CH. Additionally, the decrease in electronegativity for silicon compared to carbon (Si en = 1.74[52]) means that silicon-hydrogen bonds usually have reversed polarity when compared to CH; these compounds are formally hydrides. The electron rich hydrogen, combined with this relatively weak bond, allows for facile application by several methods. Hydrosilanes are extremely versatile functional groups, undergoing a wide variety of reactions to form new bonds to silicon.

1.3.2 Nucleophilic Substitution

Unlike protons on carbon, hydrosilanes can undergo nucleophilic substitution. For example, hydrolysis of hydrosilanes by adventitious water is a well known challenge with such silanes (Scheme 1.2). The rate of the hydrolytic process is exquisitely dependant on steric factors at the silicon nucleus. For example, silane gas (SiH_4) is pyrophoric, and in the presence of any water rapidly (and

explosively) reacts to form silicic acid, $Si(OH)_4$. The significantly more hindered compound triphenylsilane, by comparison, undergoes hydrolysis only very slowly, and is a stable solid at room temperature. The rate of hydrolysis can also be increased by increasing, or greatly decreasing, pH.

Scheme 1.2: Hydrolysis of hydrosilanes

The rate of nucleophilic substitution at silicon can be greatly enhanced by the addition of an activating agent. Usually, these are nucleophilic species that facilitate conversion of tetracoordinate silicon to produce extracoordinate silicon species. Typical activating agents are fluoride and amines such as imidazole and *N*,*N*-dimethylaminopyridine.[53, 54] Pentacoordinate silicon is much more susceptible to nucleophilic attack than the corresponding tetracoordinate species, and so the addition of an activating agent to electrophilic silicon greatly increases reaction rates in the presence of nucleophiles. In the case of hydrosilanes, the addition of an activating agent can allow for facile substitution of an otherwise stable functionality. This offers advantages in storage over more reactive electrophiles such as chlorosilanes. With respect to safety, it should be noted that this benefit can be offset by the production of H_2 should nucleophilic substation, particularly by water, be initiated inadvertently.

1.3.3 Pt Catalyzed Hydrosilylation of Alkenes

Hydrosilylation, the addition of a silicon hydrogen bond across a π-bond, is a mainstay of organosilicon chemistry. This reaction is most frequently applied to alkenes, and represents a facile method for the synthesis of silicon-carbon bonds:[55] it should be noted that hydrosilylation of C=X (X = O, N) has been exploited in organic synthesis.[51] While radical hydrosilylation is known,[56] transition metal catalyzed hydrosilylation is a much more commonly employed synthetic method. Spier's catalyst, hexachloroplatinic acid in isopropanol,[57] and more recently Karstedt's catalyst[58] (Figure 1.3) have become mainstays in synthetic organosilicon chemistry.

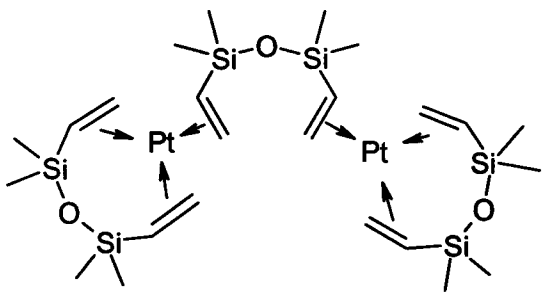


Figure 1.3: Karstedt's catalyst: Pt_2(divinyltetramethyldisiloxane)$_3$

Platinum catalyzed hydrosilylation demonstrates good regioselectivity: silicon will normally add to the least sterically hindered carbon, although selectivity for the opposite regioisomer is known.[59] The regioselectivity and yield of hydrosilylation reactions are generally high, enough so that the reaction has

been utilized in the synthesis of carbosilane dendrimers.[60] Platinum catalyzed hydrosilylation also exhibits very good functional group tolerance: halogens, esters, acetals and (in many cases) amines are compatible. The high yields, specificity and functional group tolerance make hydrosilylation the current method of choice for the derivatization of siloxane materials.

1.3.4 Activation Using Tris(pentafluorophenyl)borane

Tris(pentafluorophenyl)borane (TPFPB) is a Lewis acid, comparable in strength to boron trifluoride.[61] Unlike trihaloboranes, the stable nature of the B-C bond in TPFPB minimizes problematic side reactions, making this catalyst applicable to a much broader range of systems and transformations. As an example, TPFPB has found use as a polymerization catalyst in aqueous dispersions[62] and as a co-catalyst for Zeigler-Natta synthesis of polyolefins.[63] More recently, it has been found that the use of TPFPB in the catalytic activation of hydrosilanes allows for a number of synthetically useful reactions that shall be examined below.

1.3.4.1 Hydrosilylation

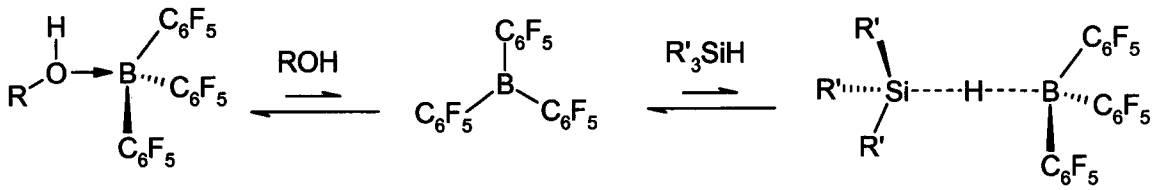
The application of TPFPB catalysis of hydrosilane reactions for organic transformations has been explored by Piers and coworkers.[64] The hydrosilylation of aromatic aldehydes, ketones and esters was found to proceed in high yields in the presence of 1-4% catalyst loading. Unlike most Lewis acid catalyzed

reactions of carbonyl compounds, the reaction did not appear to proceed through the activation of the carbonyl group: more basic C=O compounds exhibited decreased reactivity.[64] This suggests that the reaction proceeds fastest in the presence of unbound catalyst, pointing to a complex with activated SiH as the reactive species. Further investigations confirm that the key reaction step is activation of the Si-H bond by TPFPB, and suggest this reaction proceeds via hydride abstraction by boron, with subsequent carbonyl reduction.[65] Once activated, the complex can efficiently participate in the hydrosilylation of thioketones,[66] imines,[67] and olefins.[68]

1.3.4.2 Dehydrogenative Coupling to Alcohols

It has been shown that TPFPB is also an effective catalyst for the silylation of alcohols. At a 2 wt% catalyst loading, various tertiary silanes were found to dehyrogenatively couple with hydroxyl groups to produce silyl ethers.[69] As in the hydrosilylation of carbonyls, the key reactive species is proposed to be borane activated Si-H, which is consistent with the somewhat counterintuitive observation that reaction rate is inversely related to number of substituents at the alcohol: 3° > 2° > 1°. Primary alcohols bind the catalyst most effectively, and so leave the lowest proportion of catalyst available to activate hydrosilanes. The process is thus best understood as an equilibrium, first described by Piers, that applies to the activation of hydrosilanes in the presence of Lewis bases (Scheme 1.3). These studies also seem to indicate that silylation of alcohols is preferred

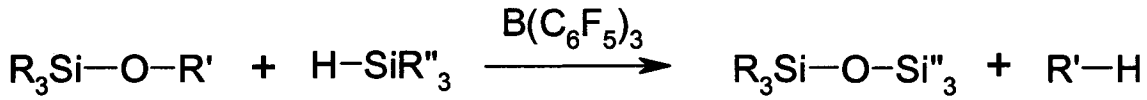
over hydrosilylation of π-bonds: the reaction proceeded in the presence of esters and ketones, as well as alkenes, alkynes and alkyl halides, demonstrating broad functional group tolerance.



Scheme 1.3: SiH Activation by Boron in the Presence of a Lewis Base

1.3.4.3 Dehydrocarbonative Coupling

The first report on TPFPB activated Si-H reduction of carbonyls contains the following sentence: "Limitation of the silane reagent to 1 equiv was essential for clean reactions since further reduction of the silyl ether or silyl acetal products was observed when excess silane was present."[64] This was occasioned by the observation that the resultant silyl ether products could be further reduced to the corresponding alkanes. While this was perceived as a limitation by Piers, the process has since been used synthetically to produce alkanes from corresponding oxy-functional compounds.[70-72] To the organic chemist, the disiloxane produced by this reaction is simply a byproduct to be removed. From the perspective of a silicon chemist, however, this reaction can be seen as a dehydrocarbonative coupling to form siloxanes(Scheme 1.4).

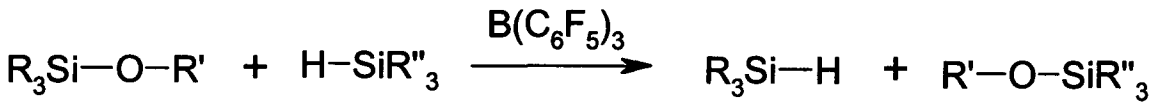


Scheme 1.4: Dehydrocarbonative Coupling of Disiloxane

Though TPFPB is able to cleave siloxane bonds in some highly reactive siloxane species such as 1,1,3,3-tetramethyldisiloxane[73] and hexamethylcyclotrisiloxane (D_3),[74] it is not sufficiently powerful to cause equilibration in ordinary silicones. This makes it highly attractive for synthesis of new siloxane bonds using the dehydrocarbonative coupling strategy. That is, unlike the problems of redistribution of silicone polymers that can be initiated by acid or base, such reactions should not occur if TPFPB is used as a catalyst. In the examples previously discussed, a single silane is used for the synthesis of the initial silyl ether and its subsequent dehydrocarbonation. This leads to a symmetrical disiloxane of little intrinsic value. Given the commercial availability of various alkoxysilanes, dehydrogenative coupling to a hydrosilane bearing different substituents offers great promise for the synthesis of asymmetrical disiloxanes. Use of sufficiently small alkyl groups (ethyl, methyl, etc.) leads to gaseous by-products which are easily removed, leading to clean synthesis of compounds which are very difficult to obtain via conventional condensation methods.

To some degree, the promise of this reaction has been captured by Rubinsztajn and coworkers in the uncontrolled synthesis of polysiloxane/carbosilane copolymers.[75] This strategy has also been successfully

utilized for synthesis of pure siloxanes in aqueous emulsion, demonstrating the impressive water tolerance of TPFPB,[76] particularly when compared to other Lewis acids. In addition to the desired dehydrocarbonative coupling, they report a competing metathetic process (Scheme 1.5). This metathesis hampers control, allowing for the synthesis of three potential disiloxanes: the desired mixed siloxane, as well as the two corresponding symmetrical siloxanes. In order to explain this phenomenon, Chojnowski and coworkers invoke a two step process: hydride abstraction by boron with simultaneous formation of a silyloxonium, followed by hydride addition.[77] It should be noted that previous investigations do not report metathesis as a significant competitive process.[75, 76]



Scheme 1.5: Competing Metathetic Exchange

While symmetrical siloxanes in Chojnowski's studies were frequently the predominant product, the authors suggest that it should be possible to manipulate the synthetic outcome by controlling steric environment of the alkoxysilane The TPFPB mediated cross-coupling of alkoxysilanes and hydrosilanes is still largely unexplored, and is a promising avenue for research into controlled synthesis of siloxanes.

1.4 Thesis Objectives

While the useful and unusual properties of silicones give them a great deal of intrinsic value, full realization of their utility has not been realized: it is simply not possible to prepare, with few exceptions, large silicone polymers of well defined structures. Siloxanes have not undergone the same sort of revolution in polymer synthetic control leading to well-defined polymer architectures that has happened in other polymer fields, the chemistry of polyolefins in particular. These synthetic limitations apply to the synthesis and modification of both siloxane fluids and siloxane elastomers.

The unique reactivity of siloxane materials offers opportunities which are not available in other polymeric systems. This is particularly true of siloxane elastomers, which retain reactivity and dynamic behaviour infrequently found in organic elastomer systems. Given this, the objectives of this thesis are twofold:

1. Exploit the well understood properties and reactivity of siloxane systems to achieve synthetic control through innovative means

And:

2. Explore novel reactions in silicone chemistry to evaluate their potential for controlled synthesis of siloxane architectures.

To do so, we have examined the following systems:

Silicones which have been surface-modified with hydrophilic groups are industrially important, particularly in biomedical applications. Current methods for

surface modification suffer from non-reproducible results and a lack of understanding in the factors which affect the grafting process. In Chapter 2, we explore methods to manipulate hydrophilic domains in silicones in order to gain greater control over the interfacial characteristics of siloxane elastomers. This includes exploration of the surface morphology as influenced by the size and functionality (mono- or di-) of the grafted polymer. We further examine a system in which the co-cure of allyl functional PEO and SiH rich silicon leads to self selection of a hydrophobic interface, with sequestration of hydrophilic domains at the interior of the elastomer.

Silicone elastomers have been explored as substrates for the delivery of compounds such as drugs, catalysts and enzymes. Devices of this type utilize the interior of the elastomer to sequester these species. Unfortunately the inability to simultaneously control the interfacial characteristics of the elastomer limits the practical application of this concept. In Chapter 3, we build on the themes explored in Chapter 2, and investigate methods for the stratification of siloxane elastomers. A strategy is proposed which takes advantage of the behaviour of silicones and various substrates in different solvents to provide or decline a mechanism of transport to the interior of the elastomer. This concept is explored to direct reactions exclusively to the surface of the elastomer, followed by determination of the availability of remaining interior functionality.

Silicone carbohydrate copolymers offer potentially interesting routes to biocompatible polymers, however available reactions to join the two are limited.

Chapter 4 examines the feasibility of direct silyl ether linkage of silicones and carbohydrates; a strategy normally avoided due to hydrolytic instability. Applying the well understood methods of protecting group chemistry to modified silicones permitted an investigation of the reactivity and stability, and ultimately synthetic utility, of hindered dialkylchlorohydrosilanes.

While the dynamic and reactive nature of silicones is responsible for their valuable properties, these same characteristics severely limit the control available in the synthesis of siloxane materials. The ability to synthesize explicit siloxane architectures would not only allow for a narrower distribution of eventual properties, but it could also lead to previously unavailable silicone architectures. Materials of this type would expand our understanding of the relationship between structural features and physical properties. Chapter 5 examines the tris(pentafluorophenyl)borane catalyzed dehydrocarbonative coupling of hydrosilanes and alkoxysilanes, as this reaction has not yet been fully explored as a synthetic method for new siloxane bonds. Of particular interest is the development of methods to exert control over this reaction, especially given the noted steric dependence of the catalyst in other transformations.

Finally, Chapter 5 explores the functional group tolerance of the dehydrocarbonative coupling. Functional silicone materials are industrially very important due to their use in a wide variety of applications, particularly in interfacial control. The ability to assembly functional, precise branched siloxane moieties could allow for the synthesis of interfacial agents with a much narrower

range of properties. Furthermore, this could lead to additional insight into a reaction which is still not fully understood.

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Chapter 2: Simple Strategies to Manipulate Hydrophilic Domains in Silicones*

David B. Thompson, Amanda S. Fawcett and Michael A. Brook

2.1 Abstract

Hydrophilic silicone polymers offer advantageous properties in a variety of applications. However, it is not always straightforward to control the placement of hydrophilic domains in a hydrophobic silicone elastomer. A facile method for the preparation of poly(ethylene oxide)(PEO)-modified PDMS elastomers is described. Hydrosilane rich elastomers are fabricated by adding poly(hydromethylsiloxane) to a standard addition cure elastomer formula. After curing the elastomer, the silicones can be functionalized using hydrosilylation with mono- and di-allyl poly(ethylene oxide) of varying molecular weights to give PEO-rich silicone surfaces. The efficiency of the grafting process, as measured by PEO on the surface, depends both on molecular weight and functionality of the PEO. By contrast, when the allyl functional PEO is added directly to the

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elastomer preparation (co-cure), silicone elastomers with internal PEO domains are formed: SiH rich polymers present preferentially at the external interface.

2.2 Introduction

The high hydrophobicity of silicones can complicate their use in some applications. For example, proteins can undergo denaturation in contact with silicones.[1] In such cases, the siloxane can be modified to include a hydrophilic domain. This is typically accomplished by functionalizing the silicone with a hydrophilic polymer such as poly(ethylene oxide)(PEO). Silicone surfactants of this type have found widespread use as stabilizers for polyurethane foams, and have been investigated as a structurant to prepare siloxane elastomers for biomaterials applications.[2] This can be done externally, allowing for the presentation of a hydrophilic domain at bio-interfaces, or internally, where PEO domains and channels within the elastomer can allow the incorporation of hydrophilic molecules for drug delivery.[3]

Although several routes to PEO-modified silicone elastomers have been described,[2, 4, 5] we were interested in developing general methodologies that will allow for the facile functionalization of siloxane elastomers internally or externally using the same feedstocks. Such materials could have application as biomaterials, optionally with a facility to deliver drugs. Several strategies are available to prepare such materials, including RTV condensation of alkoxysilane

modified PEO. However, given the commercial availability of mono- and diallyl-ethers of low molecular weight PEO (< 2000 MW, also known as poly(ethylene glycol)(PEG)) a direct hydrosilylation route was chosen.

Several features of this route to grafted PEO polymers are attractive. PEO is not very soluble in silicone, a property that can be exploited to direct reaction to interfaces. The ability to control degree of functionality at one or both ends of the PEO polymer permits independent control of crosslink density and total PEO content. Finally, any residual OH or allyl groups can be used for subsequent functionalization. We describe below strategies to 'graft in' (co-cure) and 'graft to' (post-cure) silicone elastomers with PEO.

2.3 Results and Discussion

2.3.1 Synthesis of hydride functional PDMS elastomer 1

Sylgard 184 is a commercially availably platinum-cure kit for the preparation of non-functional polydimethylsiloxane elastomers. The kit consists of two parts, a 'base', containing vinyl functional siloxanes and platinum catalyst, and a 'curing agent' containing hydride functional siloxanes. The pliable, transparent elastomers produced by this kit are a commonly used starting material for investigations into the modification of silicone rubbers, [5, 6] particularly those associated with biomaterials.[7-10] This elastomer is crosslinked via hydrosilylation of vinyl silicones with hydrosilicones. It is possible to directly

modify the properties of the silicone during cure by adding compounds with functional groups capable of hydrosilylation. For example, the addition of vinyl- or hydrosilyl- functional materials to the uncured Sylgard silicones will ultimately lead to their incorporation into the resulting elastomer via covalent bonds.

We chose to utilize this approach to introduce poly(ethylene oxide)(PEO) into or onto silicone elastomers. As allyl-modified PEO is commercially available or readily synthesized, it was necessary to ensure the starting silicone materials had sufficient SiH functionality to permit covalent tethering. Therefore, addition of poly(hydromethyl)siloxane (PHMS; DC 1107 fluid) to the conventional Sylgard kit was examined in order to prepare hydride functional PDMS elastomer **1**.

It was found that a ratio of 10 parts (by weight) elastomer base to 1 part cure to 1 part PHMS gave high levels of Si-H functionalization both on the surface and interior of the elastomer (by ATR-FTIR – interior measurements were made after sectioning the cured elastomer). As expected, addition of PHMS affected both the cure-time and physical properties of the resultant elastomers; adding higher proportions of PHMS (10:1:2, 10:1:1.5, etc.) gave elastomers which were unacceptably brittle. Functionalization could be maximized by storing the resulting elastomers for several days under vacuum. This prevented undesired hydrolysis of SiH groups by adventitious water during the period in which the Pt catalyst remained active.

2.3.2 Post-cure process for PEO functional PDMS elastomers

In a procedure related to those previously described by our group,[2, 11] SiH rich elastomers **1** were modified post-cure with mono and di-allyl functional PEO of different molecular weights. The procedure involves a biphasic system whereby excess PEO in THF solution was reacted at the interface with SiH groups on the non-dissolved, functional elastomer. As in any 'grafting-to' approach, it was necessary to consider the factors that affect the graft density of PEO at the surface. The steric bulk of grafted PEO can hinder the approach of additional PEO chains, resulting in lower PEO reaction at the surface. These effects can be ameliorated somewhat by shifting to a less bulky (lower MW) polymer, although this runs the risk of reducing the total mass of hydrophilic polymer that will be bound at the interface. In order to better understand the interplay between these factors, three different molecular weights of PEO (250, 550 and 1100 MW) were used in these experiments. Both the mono- and di-allyl versions of each size polymer were reacted, from which conclusions could be drawn about the presence of loops and chains (di-allyl, **L**, mono-allyl, **C**, Figure 2.1) of PEO at the silicone interface.

ATR-FTIR surface characterization was utilized to quantify the results of these experiments. Typically, this method involved normalization of the signal of interest against the C-H methyl stretch from PDMS; where necessary, signals from a 'blank' were also background-subtracted. It was found that most (80-95%) of the surface SiH groups were consumed between the hydrosilylation and

alcoholysis/hydrolysis during workup. At the same time, significant increases in the CH_2 stretch for PEO were observed for all reacted disks. The efficiency of grafting (the number of surface grafted chains per surface area) was affected by both the molecular weight of the polymer, and whether mono- or di-functional PEO was used. The results were analyzed by determining total amount of PEO on the surface and the relative grafting efficiencies for each polymer length could be determined by dividing the normalized signal strength by the number of ethylene oxide units per polymer (MW 250 = 4, MW 550 = 11, MW 1100 = 23; all surface areas were ~1 cm^2).

For the post-cure grafting of mono-allyl PEO, the results followed expected trends. The total amount of PEO at the interface increased with polymer size. This increase was not linear: 250 MW and 550 MW polymers showed a total surface PEO value of 60% and 93%, respectively, of that of the 1100 MW polymer. Examination of grafting efficiency (number of chains grafted to the surface, Table 2.1) also showed a strong dependence on molecular weight. The 250 MW polymer had the highest grafting efficiency, whereas the 550 grafted at only 57% of this value. The 1100 MW polymer showed half the grafting efficiency of the 550 monoallyl PEO. Based on these results, the 550 MW polymer shows the best compromise between grafting efficiency (number of chains grafted) and total mass of PEO polymer at the interface, whereas 1100 MW polymer shows slightly superior grafted mass of polymer at the interface.

Results for the di-allyl PEO grafted disks also illustrate that the efficiency of grafting is dependent on the molecular weight of the polymer. In this case, however, the 550 MW polymer gave the greatest yield of polymer at the interface, followed by the 250 MW. As with the mono-allyl polymers, grafting efficiency decreased with increasing molecular weight of PEO.

A comparison of grafting results for mono- and di-allyl polymers provides information about the degree to which 'chains' and 'loops' contributed to the observed surface properties. Interestingly, the 250 MW di-allyl polymer grafted slightly more efficiently than its mono-allyl analogue. This small difference is attributed to a component of 'unstable' grafting of PEO with the mono-allyl polymer through the free hydroxyl group at the non-allyl terminus. In the presence of platinum catalyst, it is possible for hydroxyl groups to dehydrogenatively couple to hydrosilane functionalities. While reaction with alkenes is highly favored, it is likely that a small percentage of the mono-allyl polymer underwent this process, grafting 'upside down'. As the resulting alkoxysilane groups are not stable to solvolysis/hydrolysis, they would be cleaved during the subsequent washing protocols. At any rate, the very high graft efficiency of the di-allyl polymer suggests that di-reaction (formation of 'loops' at surface) did not take place to a significant degree during the grafting process (Figure 2.1).

For the post-cure modification with 550 and 1100 MW di-allyl PEO, fewer chains grafted to the surface than the mono-allyl versions of the same molecular

weight (Table 2.1). This result suggests that, to differing degrees, the polymers were able to doubly react at the surface, forming loops (**L** Figure 2.1). The grafting efficiency of the 550 di-allyl polymer was approximately 20% lower than that of its mono-allyl analogue, suggesting that this surface is comprised of a mix of chains and loops at the interface (Figure 2.1). The grafting efficiency of the longest di-allyl polymer, meanwhile, was only 60% of the mono-allyl PEO of the same size. Reaction of both allyl groups on the diallyl PEO would give an efficiency of 50%: The value of 60% suggests that the surface also contains a few straight chains. However, di-reacted loops seem likely to comprise the bulk of the hydrophilic polymer at the interface. These results suggest that there is a size requirement for double reaction of PEO polymer at the silicone surface; the larger PEO polymers cast a larger shadow leading to a significant enhancement in the rate of intramolecular grafting (second allyl group on a polymer) over that for intermolecular coupling (first of two allyl groups on PEO). The strategy using low MW PEO is particularly interesting, as it provides the possibility of secondary grafting to the residual allyl groups (**C** Figure 2.1).

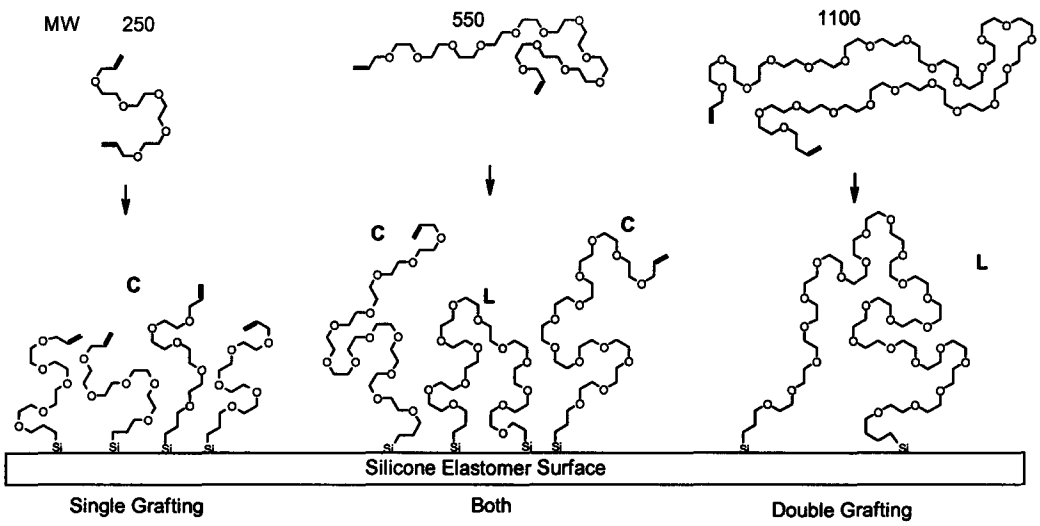

Figure 2.1: Schematic showing preference for double grafting with increasing PEO molecular weight.

Table 2.1: Results of elastomers prepared via post-cure methodology

Property	1	Control[f]	Mono Allyl PEO			Di Allyl PEO		
MW (g/mol)	NA	NA	250	550	1100	250	550	1100
Contact Angle (°)[a]	97.5	105	95.5	100.3	99.4	102.3	101.9	102.7
Roughness (nm)[b]	19.90	15.08	17.89	20.91	11.19	10.57	20.86	11.51
SiH (by ATR-IR)[c]	0.25	0.263	0.019	0.017	0.053	0.062	0.016	0.034
PEO[d]	na	0	0.112	0.172	0.185	0.122	0.145	0.113
Graft Efficiency[e]	na	0	0.028	0.016	0.008	0.031	0.013	0.005

a: Sessile water drop.
b: Veeco profilometer rms roughness (Rq)
c: ATR-FTIR signal height for SiH stretch normalized against CH_3 stretch
d: ATR-FTIR signal for CH_2 stretch normalized against CH_3 stretch with background subtraction
e: PEO value divided by number of PEO units per chain (4 for 250, 11 for 550, 23 for 1100)
f: control sample was exposed to identical reaction conditions and washing protocols as the reaction with 550 mono-allyl polymer, but in the absence of Pt catalyst

2.3.3 Co-cure process for PEO functional PDMS elastomers

Grafting of PEO to silicone elastomers was also attempted in a co-cure fashion; SiH functionalization, PEO functionalization and platinum catalyzed hydrosilylative curing of the PDMS elastomer were undertaken concurrently (Table 2). In this case, it was anticipated that the PEO would be distributed in homogeneous domains throughout the final rubber. To permit comparison with the compounds described above, mono- and di-allyl PEO of varying molecular weights were independently added to Sylgard 184 base containing excess PHMS, in the ratio of 10:1:1 used previously.

It was discovered that the addition of 0.05 parts PEO to the 10 parts base, 1 part curing agent, 1 part PHMS mixture allowed for the best compromise of functionalization, incorporation of PEO, cure times, and physical properties. Additionally, due to the extreme differences in polarity between PEO and PDMS, it was found that addition of 0.5 parts dichloromethane was necessary to facilitate incorporation of PEO into the mixture.

This protocol led to significantly rougher surfaces when compared with the post-cure materials described above. This difference is attributed to the altered kinetics of the cure and the resulting effect on degassing/solvent evaporation: control experiments demonstrated that roughness did not arise from the presence of the solvent alone. In essence, bubbles of gas escaping under vacuum are 'captured by crosslinking' at the surface. The differences in

roughness suggest that cure is inhomogeneous, with a greater degree of crosslinking occurring at the external surface. While notable, this roughness is not believed to be a contributing factor to the distribution of PEO within the silicone matrix. Additionally, while there is variation in the properties of the co-cure silicone-PEO elastomers between the various hydrophilic polymers used, no correlation between polymer size/functionality and resulting properties was discernable.

Unlike the post-cure modified samples, these co-cure elastomers were not optically transparent, but rather slightly cloudy and translucent, which is attributed to the presence of discrete PEO domains within the siloxane. ATR-FTIR, however, showed no evidence for PEO on the surface. Additionally, unlike the post-cure results, these reactions were not accompanied by a decrease in SiH functionality at the surface. Instead, in all cases the relative concentration of SiH groups at the surface was significantly larger than in the control experiments. These observations suggest that the PEO is completely sequestered within the interior of the elastomers during the cure. This conclusion was further confirmed by cutting one of these disks (550 mono-allyl PEO co-cure) in half and measuring the ATR-FTIR spectrum of the interior of the disk. The spectrum showed a corrected PEO value of 0.163, with a SiH value of 0.191. This PEO value for the inside is comparable to the surface value for the post-cure surfaces, while the SiH value is lower than that found at the surface of the SiH elastomer from part 1.

Silicones have very low surface energy.[12, 13] As a consequence, and facilitated by their high flexibility (Tg ~ -123 °C), silicones generally migrate to air interfaces. Because of this, even hydrophilically modified surfaces, as in the post-cure samples described above, have very high contact angles: small amounts of silicone bleed to the air interface. We note that contact angles are affected by surface roughness,[2] by the chemical constituents of the surface, and orientation at the interface. For example, contact angles of PEG block co-polymers were highly dependent on the solvents to which the polymer was exposed and the hydrophobicity of the surface.[14] Thus, while it is possible to synthetically direct PEO only to the interface with our post-cure methodology, the resulting hydrophilic character will manifest itself only when the object is submerged in polar, typically aqueous, media, but not in air.

A similar effect is observed with silicone elastomers prepared with the co-cure method: the surfaces are hydrophobic and deficient in PEO, because PDMS and PHMS constituents are directed to the air interface. Interestingly, in this case, however, the silicones partition differently at the surface. ATR-FTIR demonstrated a relative increase in SiH functionality over PDMS when compared to the control. These results can only be explained by preferential migration of SiH polymer to the surface when sequestering PEO in the interior, perhaps as a result of the reduced steric bulk of each monomer unit. The resulting 'inside out' elastomers with a hydrophilic interior and an SiH rich exterior may offer a

potential route to asymmetrically structured siloxanes by subsequent reactions with other olefinic groups.

Table 2.2: Results of elastomers prepared via co-cure methodology

	1	Control[e]	Mono Allyl PEO			Di Allyl PEO		
MW (g/mol)	NA	NA	250	550	1100	250	550	1100
Contact Angle (°)[a]	97.5	103.6	107.6	103.8	106.5	105.8	106.5	108.6
Roughness (nm)[b]	19.90	44.3	224.24	348.39	197.21	532.67	778.47	687.23
SiH (by ATR-IR)[c]	0.25	0.291	0.484	0.424	0.396	0.494	0.367	0.37
PEO[d]	na	0	0.012	-0.001	0.015	0.005	0.001	-0.008

a: Sessile water drop.
b: Veeco profilometer rms roughness (Rq)
c: ATR-FTIR signal height for SiH stretch normalized against CH_3 stretch
d: ATR-FTIR signal for CH_2 stretch normalized against CH_3 stretch with background subtraction
e: The control sample was an elastomer prepared under identical conditions (base, curing agent, PHMS, solvent) but without the addition of PEO

2.4 Experimental Section

Mono-allyl PEO (250MW, 550MW, and 1100MW) were a gift from Clariant. Sodium hydride, allyl bromide, diethylene glycol dimethyl ether, and Karstedt's catalyst (2% solution in xylenes) were purchased from Aldrich. The Sylgard 184 kit and polyhydromethylsiloxane (PHMS)(DC1107, 30Cs MW ~2000) were purchased from Dow Corning. Sylgard is a platinum cured silicone elastomer filled with between 10-30% Me_3Si-modified, hydrophobic silica. Hexanes, dichloromethane, and tetrahydrofuran were purchased from Caledon

and dried using pressurized alumina columns. Absolute ethanol was purchased from Industrial Alcohols and was used without further purification.

NMR spectra were recorded using Bruker Biospin AV200 spectrometer (at 200 MHz for protons). Infrared spectra were recorded on a Bio-Rad FTS-40 attenuated total reflection Fourier transform IR using a horizontal cadmium selenide crystal. Surface roughness was measured by an interferometer, which generates a 3D profile (Veeco WYKO NT1100 optical profiler).

Synthesis of 250, 550, and 1100MW DiallylPEO

In a typical synthesis (shown for mono allyl PEO MW 250): mono allyl PEO (2.05 g, 8.22 mmol) and THF (40 mL) were combined in a 100 mL round-bottomed flask, and stirred with a magnetic stir bar. Sodium hydride (0.63 g, 26.2 mmol, excess) was slowly added over a period of 15 minutes and the resulting mixture was left to stir for an additional 15 min. Excess allyl bromide (2.77 mL, 32.0 mmol) was added dropwise and the reaction was stirred for 30 min. The resulting mixture was gravity filtered and excess solvent removed using a rotary evaporator and residual solvent was removed under high vacuum overnight. Yield (250 [63%, 1.28 g, 5.15 mmol)], 550 [52%, 1.03 g, 1.88 mmol], 1100 [69%, 1.39 g, 1.26 mmol].

250MW: ^{1}H NMR ($CDCl_3$) δ = 5.87 (m, 2H); 5.19 (m, 4H), 4.01 (d, 4H, J = 5.6 Hz), 3.63-3.58 (m, 19H).

550MW: ^{1}H NMR ($CDCl_3$) δ = 5.87 (m, 2H); 5.19 (m, 4H), 4.01 (d, 4H, J = 6.0 Hz), 3.63-3.58 (m, 48H)

1100MW: ^{1}H NMR ($CDCl_3$) δ = 5.87 (m, 2H); 5.19 (m, 4H), 4.01 (d, 4H, *J* = 6.2 Hz), 3.63-3.58 (m, 96H)

2.4.1 Preparation of SiH functionalized PDMS

In a beaker, Sylgard 184 base (11.30 g), Sylgard 184 curing agent (1.13 g), and DC1107 (1.13 g) were sequentially combined. The solution was stirred vigorously and 11.60 g was transferred to a 100mm x 20mm Petri dish. The dish was placed under vacuum for three days to cure at room temperature. After initial foaming, the silicone cured to an optically transparent, bubble free elastomer. Approximately 45 disks (0.64cm diameter, ~ 0.22 cm thick) were punched out of the surface and washed with THF (5 x 5 mL x 30 sec) to remove any excess DC1107. The disks were then dried under high vacuum for 24 h.

ATR-FT-IR: 2961; 2163 (Si-H); 1050 (Si-O-Si); 1070 cm^{-1}

Post-cure synthesis of PDMS-PEO elastomers with 250, 550, and 1100MW Mono- and Di-Allyl PEO

In a typical synthesis PEO (0.10 g), THF (3.0 mL), and 5 x SiH functionalized PDMS elastomer disks (*ca.* 63.0 mg/disk) were combined in a sample vial and stirred for one hour to allow the system to reach equilibrium. Karstedt's catalyst (10 μL, 2% solution in xylenes) was added and the vials were left to stir for 16 h. The disks were washed with H_2CCl_2 (3x5mL), EtOH (3x5mL),

water (3x5mL, after which PEO was not detected in the wash water), EtOH (3x5mL), and H_2CCl_2 (3x5mL) and dried under vacuum for 24 h.

ATR-FT-IR: 2961; 2873; 2163 (Si-H); 1050 (Si-O-Si)

Co-cure synthesis of PDMS-PEO elastomers with 250, 550, and 1100MW Mono- and Di-Allyl PEO

In a typical synthesis (shown for mono allyl PEO MW 250), Sylgard 184 base (2.01 g), Sylgard 184 curing agent (0.20 g), DC1107 (0.20 g), and a solution of PEO (0.01 g) in DCM (0.10 g) were combined sequentially in a beaker. Simultaneously, a control experiment was prepared wherein the PEO was omitted. The solution was stirred vigorously and ~1g was transferred to a 35mm x 10mm Petri dish. The dish was then placed under vacuum for four days to cure. Approximately 7 disks of 0.65cm diameter x 0.13cm thickness, *ca.* 42 mg/disk) were punched out of each surface and washed with H_2CCl_2 (3x5mL), EtOH (3x5mL), water (3x5mL, after which PEO was not detected in the wash water), EtOH (3x5mL), and H_2CCl_2 (3x5mL) and dried under vacuum for 24 h.

ATR-FT-IR: 2961; 2873; 2163 (Si-H); 1050 (Si-O-Si)

2.5 Conclusion

We have developed strategies to allow the preparation of structured siloxane-poly (ethylene oxide) elastomers. The properties of the elastomers are controlled by exploiting the interfacial properties of silicones, the locus of grafting and the extent of reaction. The single step synthesis of hydride rich PDMS elastomers using commonly available starting materials can be simultaneously (co-cure) or sequentially (post-cure) used to incorporate mono- and di-allyl PEO. With the co-cure methodology, PEO segregates to the inner part of the elastomer. Simultaneously, the PHMS preferentially migrates to the outer surface, when compared to PDMS. For elastomers prepared via post-cure modification, efficiency of grafting is inversely proportional to PEO MW, although more EO units end up on the surface with increasing molecular weight. With di-allyl PEO, the degree to which 'loops' of di-reacted polymer are present at the interface is also heavily dependant on polymer size: of the three polymers examined, the highest molecular weight 1100 MW di-allyl PEO seems to mostly form polymer loops, though at the expense of lower graft densities: the 250 MW polymer, appears to exclusively form singly reacted chains. Reactions with the remaining allyl groups may offer new routes to layered polymer surfaces.

2.6 Acknowledgements

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Chapter 3: Stratified Silicone Elastomers Using Solvent Directing Effects

David B. Thompson, Ryan Longenecker, Jordan N. Fortuna and Michael A. Brook*

3.1 Abstract

While of demonstrated broad utility, the use of silicone elastomers can be complicated by undesirable external hydrophobicity and difficulties in controlling the internal morphology. A simple and generic methodology is presented that permits independent functionalization of the exterior and interior of silicone elastomers. By carefully selecting reaction solvents and substrates, it is possible to provide or inhibit a mechanism of transport for a reagent to the interior of the elastomer. Using a good solvent/substrate match, hydrosilane rich elastomers were modified throughout with a hydrophobic aromatic residue. Using mismatched solvent/substrate pair, the same elastomers could be modified explicitly at the external surface with poly(ethylene glycol), creating PEG-surface, SiH-core elastomers. The residual interior SiH groups could be subsequently modified in a variety of chemically distinct modes in the appropriate solvent. The formation of internal amine complexes, followed by hydrolytic crosslinking

(nucleophilic substitution); grafting of hydrophobic moieties by hydrosilylation, or deposition of platinum metal colloids within the elastomer matrix are described.

3.3 Introduction

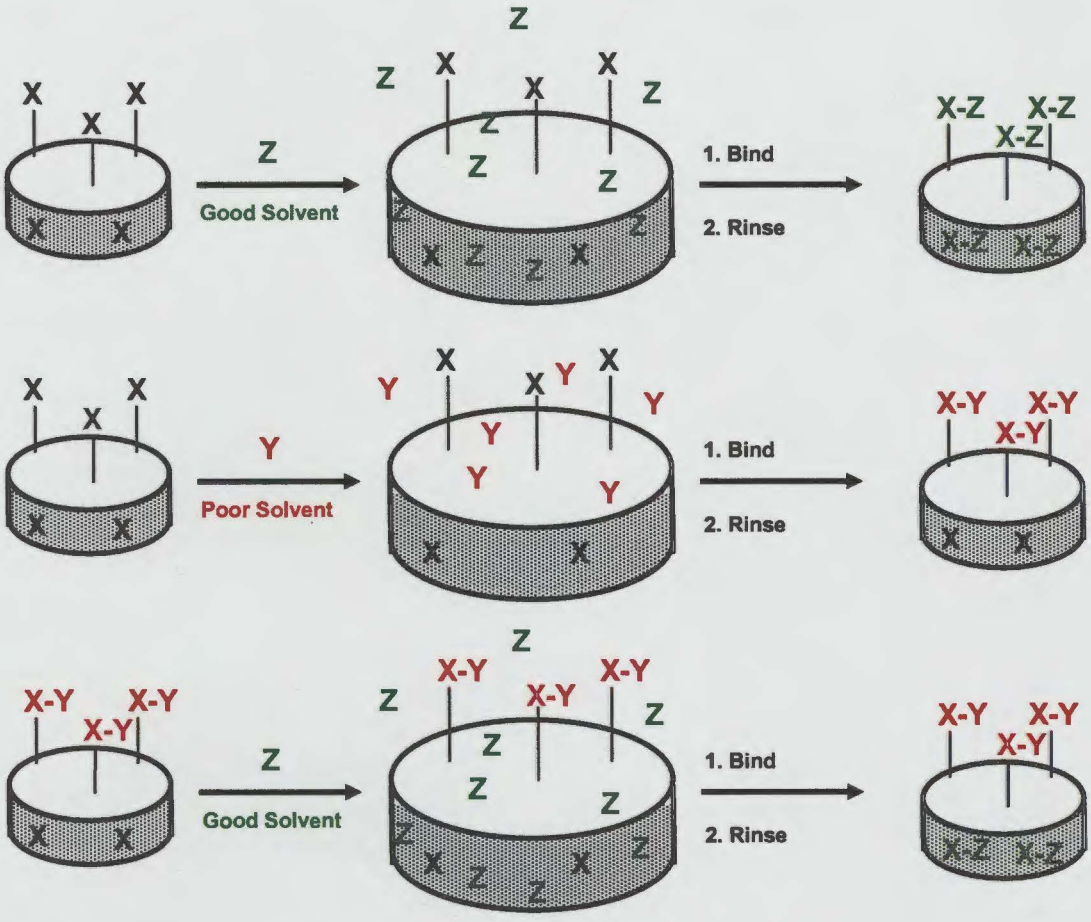
The manipulation and exploitation of solvent parameters is a traditional strategy for controlling the outcome of chemical reactions. A properly chosen solvent can accelerate reactions, increase yields and simplify purification. Controlling the interactions of reagents, particularly by use of poor solvents (i.e. hydrophobic compounds in water)[1, 2], can lead to enhanced reaction rates and selectivity.[3, 4] Although these are standard tools in organic chemistry, they are far less utilized in synthetic polymer chemistry.

Polydimethylsiloxane (PDMS) elastomers possess a range of inherently interesting properties, including thermal stability, oxygen permeability and high hydrophobicity. Other properties, such as their low toxicity, oxygen permeability and transparency make them attractive in biological applications, particularly in the eye.[5] In order to decrease non-specific adsorption of proteins on the hydrophobic surface, silicones intended for use in biological applications are frequently surface-modified with hydrophilic moieties, in particular polyethers such as poly(ethylene oxide)(PEO)[6] and, in the area of contact lens science, poly(vinylpyyrolidone).[7] Some of the strategies for surface modification include direct crosslinking of mono-[5] and bis-[8] alkoxysilyl terminated PEO into PDMS

elastomers using a tin catalyst, covalent attachment of allyl functional PEO to an active SiH surface silicone elastomer via platinum catalyzed hydrosilylation[9] and non-covalent entrapment of siloxane-modified PEO.[10] Previous work in our group has demonstrated that hydrosilylation can also be used to graft functional PEO, allowing for subsequent grafting of biomolecules to the silicone surface.[6] While these various methods have proven effective for the synthesis of PEO modified PDMS, they do not permit control of the internal chemistry or morphology of the elastomer. Such control might allow the fabrication of silicone-based devices, such as sustained drug release devices (via prodrugs), and development of supported metal catalysts.

Silicones are well known to swell in the presence of non-polar solvents, often to many times their original size. Though frequently seen as a limitation,[11] this migration of solvent to the interior of the elastomer provides a mechanism to transport solvated species across the liquid/solid interface. In a good solvent, swelling of the elastomer will deliver reagents to the elastomer interior, where they can form covalent bonds to functional groups found there. If the same functional groups are present at both the exterior and interior of an elastomer, reactions in a good solvent would cause simultaneous functionalization at the exterior and interior of an elastomer. By contrast, if a reagent is relatively insoluble in a swelling solvent, it will lack a mechanism of transport across the interface to the interior of the elastomer. In this case any grafting that takes place would of necessity be limited to the external surface, preserving any

interior functionality. Using a combination of these principles it should be possible to graft a poorly solvated reagent and a highly solvated reagent sequentially. The synthesis of stratified silicone elastomers is demonstrated, taking advantage of the differential behavior of silicones and substrates in different solvent systems, which permits independent grafting reactions to the exterior surface and elastomer interior (Scheme 3.1).



Scheme 3.1: Directing effects of solvent in elastomer modification

3.3 Results and Discussion

3.3.1 Synthesis and Characterization of SiH Functional Elastomers

PDMS may be surfaced modified with hydrophilic groups using a variety of strategies.[6, 8, 9] In order to achieve the current goal of differentially functionalizing the surface and interiors of a silicone, it was first necessary to prepare an elastomer with appropriate functionalization. Silicone hydrides are versatile functional groups that can be easily distributed throughout a silicone elastomer by simply admixing an excess of SiH functional polymer into a standard addition-cured system ($R_3SiCH{=}CH_2{+}HSiR'_3 \rightarrow R_3SiCH_2CH_2SiR'_3$). Such an elastomer **1,** was prepared by the addition of PHMS (poly(methylhydrosiloxane)$(MeHSiO)_n$) to a commercially available silicone elastomer precursor, Sylgard 184.[12]

The presence of residual SiH groups in the cured elastomer, both in the interior and at the external interface, was confirmed with attenuated total reflectance Fourier transform infrared (ATR-FTIR) spectroscopy. Normalization of the *SiH* stretch intensity against the Si*CH*$_3$ stretch of PDMS allowed comparison of the surface SiH concentration between samples.‡ Sectioning the elastomers permitted an analogous analysis of the interior of the elastomer. IR spectra

‡ Signal intensity for Si*H* stretch was divided by Si*CH*$_3$ stretch to obtain normalized SiH signal ($n \geq 3$).

demonstrated that the SiH groups in the interior were present in concentrations of approximately 90% of those found at the exterior surface.

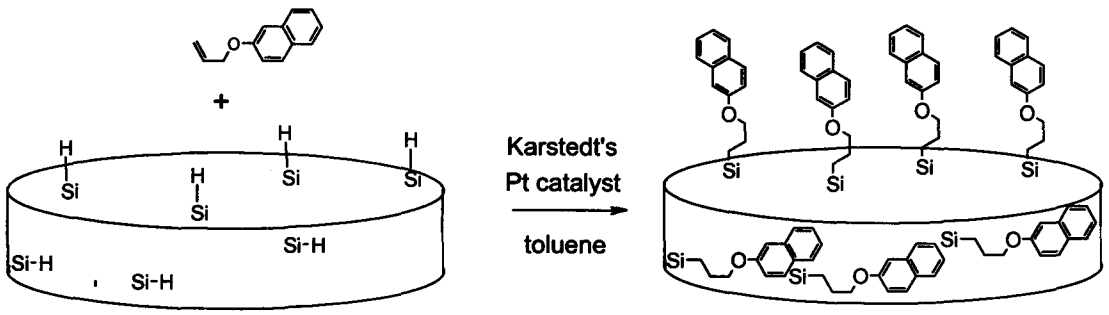
Hydrosilane groups are, under certain conditions, susceptible to hydrolytic cleavage. In order to establish the stability of our SiH rich elastomers, the SiH intensity, both inside and out, was monitored over a period of 30 days (see Supplementary Information). Comparisons were made between samples stored in a desiccator and samples stored under atmospheric humidity. All elastomers show a decrease in functionalization during the first 3 – 7 days, at both the interior and exterior of the disks. That this occurs irrespective of dry storage strongly suggests that residual crosslinking to unreacted vinyl groups continues for several days due to unexpected persistence of active catalyst. While all samples showed substantial SiH decrease over this time frame, elastomers stored under dry conditions show significantly increased surface functionalization when compared to those stored under ambient humidity. This suggests that, in addition to SiH + vinyl crosslinking, hydrolytic crosslinking (2 SiH + $H_2O \rightarrow$ Si-O-Si +H_2) is also taking place at the surface of elastomers stored under non-dry conditions. This would be greatly facilitated by the prolonged catalytic activity previously mentioned. Interestingly, the SiH content of the interior of disks stored under ambient conditions was approximately the same as those stored over desiccant, indicating that atmospheric water is unable to migrate to the interior of the elastomers. Based on these results, all elastomers **1** were stored under dry conditions until use. The high SiH functionality, both inside and out, and the

stability of these rubbers makes them ideal starting materials for stratified elastomers (see Supplementary Information).

3.3.2 Modification Throughout Elastomer with β-Allyloxynaphthalene

It was necessary to verify the availability of both interior and exterior SiH groups for grafting reactions. β-Allyloxynaphthalene, which is yellow in color, was chosen as a convenient model compound that would enter the interior of the elastomer when appropriate solvents were used. This substrate was dissolved in toluene, a good swelling solvent for PDMS. Hydrosilane functional elastomers **1** were allowed to swell in this solution for a period of several hours. In this way, the surface SiH groups were kept in contact with the substrate in solution, while the swelling of the elastomers facilitated transport of naphthyl groups to the interior of the elastomer. The addition of Karstedt's catalyst (2% solution in xylenes) initiated hydrosilylation of the allyl double bond by the elastomer bound SiH groups, grafting the β-allyloxynaphthalene via covalent bonds at both the interior and exterior of the elastomer, forming naphthyl modified elastomer **2** (Scheme 3.2). ATR-FTIR showed complete removal of the *SiH* stretches, as well as new aromatic *C=C* bending, at the surface and core of the elastomer. NMR showed presence of aromatic groups and non-silylated aliphatic carbons within the elastomer Attempts to remove residual β-allyloxynaphthalene from the elastomer by Soxhlet extraction failed: the disks remained the characteristic

golden yellow color of β-oxynaphthalene, while the extracting solution remained colorless.



Scheme 3.2: Synthesis of elastomer 3

3.3.3 Surface Modification with Poly(ethylene oxide)

The poor solubility of PEO in certain organic solvents[5, 6, 8-12] permits the preferential surface modification of SiH-rich silicone elastomers. Using hexanes, a solvent that readily swells silicones but in which PEO has very poor solubility, mono-allyl PEO (550 M_w) was grafted to the external surface using Karstedt's catalyst to give **3**. Following the hydrosilylation reaction, the disks were washed extensively with dichloromethane, ethanol and water to remove any unbound PEO and residual solvent was removed *in vacuo*. ATR-FTIR showed the disappearance of the surface *SiH* peak with a simultaneous increase in the CH_2 stretch for PEO (Figure 3.1A). Comparing the interior and exterior of the

elastomer, SiH signals decreased by 87% at the exterior, compared with only a 28% decrease in the interior† (Figure 3.1B).

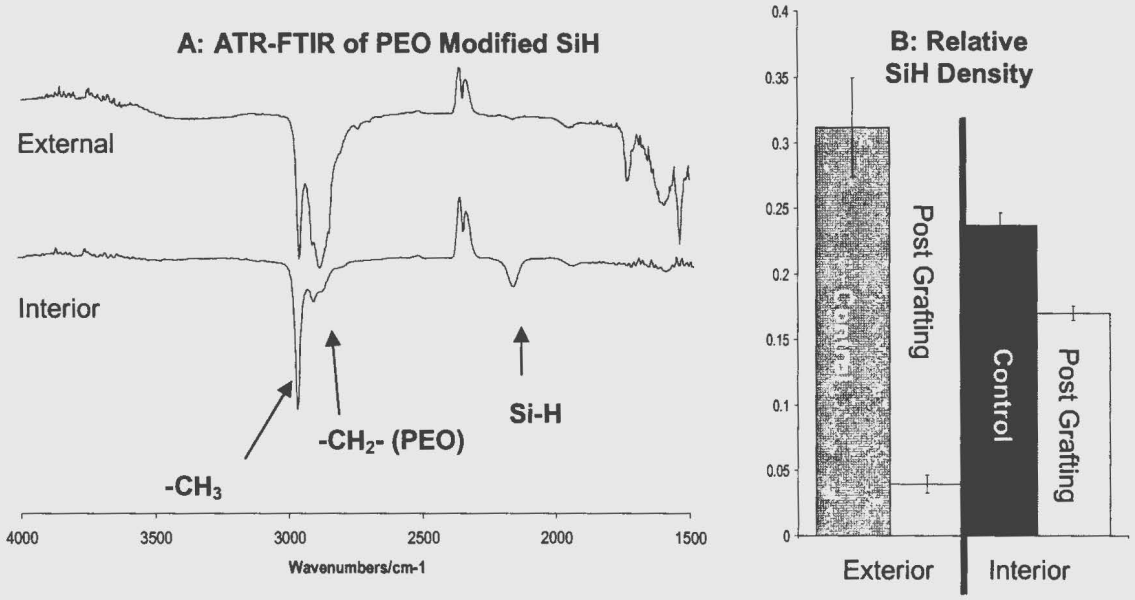


Figure 3.1: Interior and exterior of disks post grafting. ATR-FTIR (A) and % decrease (B)

PEG, relatively insoluble in hexanes, is not readily transported to the interior of the disk: no PEG signals could be seen spectroscopically in samples of the interior. The slight decrease in SiH density in the interior is attributed to adventitious water in the presence of active platinum catalyst, either during the reaction or during the post-grafting washing procedure, which can lead to

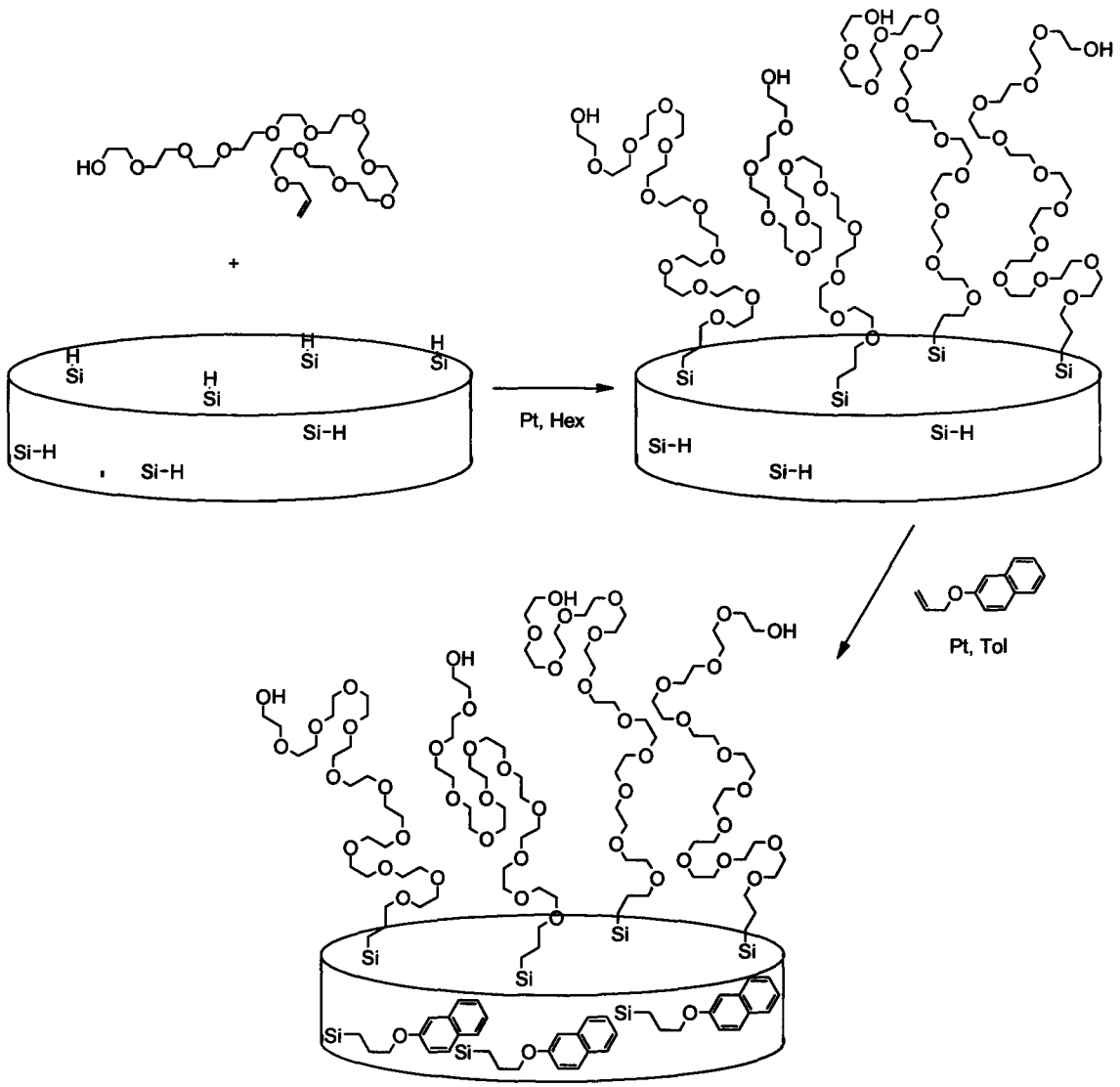
† To analyze the interior of the elastomers via ATR-FTIR, the disks were sectioned at the midpoint: approximately 1 mm for a 2 mm elastomer.

hydrolysis and, ultimately, condensation ($R_3SiH + H_2O \rightarrow R_3SiOH + H_2 \rightarrow R_3SiOSiR_3$, see also below). This process demonstrates the ability, by manipulating relative solvency, to drive reactions at the interface, but not the interior of silicone elastomers.

3.3.4 Utilization of Core Functionality

It was of interest to establish if the interior SiH groups of **3** remained available for further functionalization through hydrosilylation. Again, β-allyloxynaphthalene was chosen as a model compound for hydrophobic transport to the interior. Elastomer **3** was allowed to swell in a dry toluene solution of β-allyloxynaphthalene. Karstedt's catalyst (2% solution in xylenes) was added and the resulting mixture was stirred at room temperature for 6 hours (**Scheme 3.3**). The disks were extracted overnight in dichloromethane in a Soxhlet apparatus to remove any unbound starting material. After reaction, the resultant stratified elastomer **4** had taken on the characteristic deep yellow color of the grafted aromatic compound, while a control elastomer (same procedure lacking the platinum catalyst) remained clear and colorless (**Figure 3.2**). ATR-FTIR showed a significant decrease, but not complete removal, of the interior SiH stretch and ^{13}C MAS ssNMR revealed the presence of aromatic carbon within the elastomer. The persistence of residual SiH at the interior of the elastomer was unexpected: the same grafting to elastomers without PEG at the interface (synthesis of **2**) showed complete removal of the *SiH* signal at the interior. This result suggests that hydrophilic PEG at the interface serves to hinder the transport of

hydrophobic groups across the membrane to the interior of the elastomer; an unexpected but interesting method for additional control over transport to the elastomer core.



Scheme 3.3: Synthesis of PEG surfaced SiH elastomers and subsequent grafting of β-allyloxynaphthylene

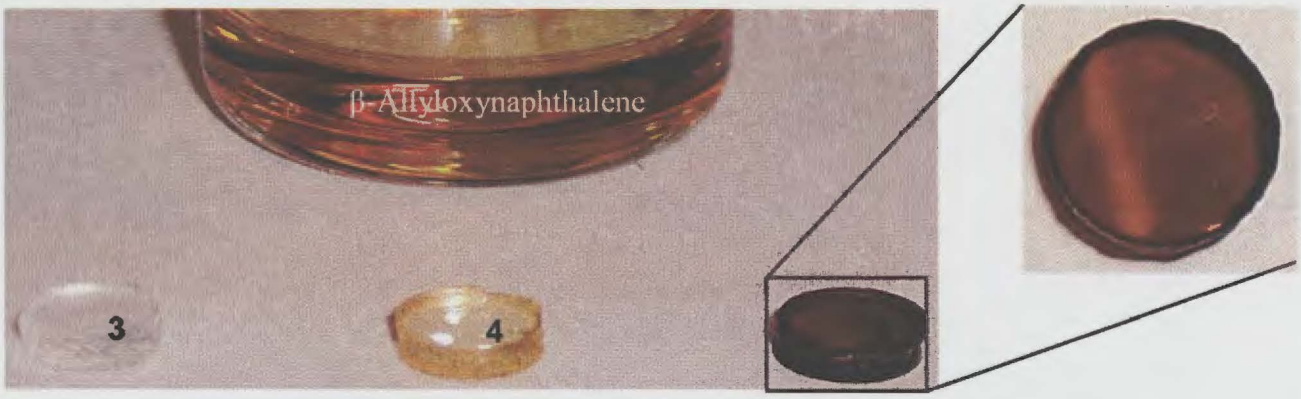


Figure 3.2: Different examples of interior functionalization for siloxane elastomers surface grafted with PEG

Hydrido-functional siloxanes are activated by platinum catalysts for hydrosilylation. However, contact with hydrosilanes can also lead to the reduction of platinum catalysts to metal nanoparticles, which can cast a yellow color into the elastomer.[13, 14] Analogous stabilized metal clusters that exhibit interesting catalytic activity[15, 16] have been described.[17, 18] It was important to establish whether the yellow color observed in the synthesis of **2** (Scheme 3.2) and **4** (Scheme 3.3; Figure 3.2) was a consequence of platinum cluster formation, or the presence of the aromatic groups. A control experiment was undertaken with Karstedt's platinum solution, which was exposed to the Si-H rich elastomer **3** in the absence of any π-bond that could be hydrosilylated. After six hours, the disks were washed with dry toluene and dried under vacuum, affording elastomers with a PEG exterior and intensely colored brown Pt colloids on the interior **5**: the ability of these SiH disks to extract ('mop up') active platinum

species from reaction mixtures may offer a convenient matrix to concentrate and recover platinum residues. Determining the degree of catalytic activity of the sequestered platinum, particularly in otherwise aqueous systems,[19] is currently under investigation. The ability to 'tune' the surface properties of these disks to suit differing systems is an attractive feature for either of these potential applications.

Hydrophobic solvents can also be used to introduce functional molecules of polarity intermediate to those of PEG and allyloxynaphthalene to the interior of silicone elastomers. This was demonstrated by swelling PEG-on-silicone elastomer disks **3** with benzylamine in toluene. After 6 hours, the resulting elastomer disks **6** were washed thoroughly with dry toluene and dried under vacuum for an additional six hours. ATR-FTIR of the disks revealed the presence of amines at both at the exterior (very strong) and interior of the elastomer. The disks also became opaque, which may indicate the formation of a complex between the amine and the silicon. The exact nature of the entrained benzylamine complex is not clear. However, it was found that the resulting product readily undergoes reaction with water.

Amines are known to activate silyl hydrides towards nucleophilic substitution,[20, 21] including by nucleophiles like water, in which case reaction leads to the creation of new Si-O-Si bonds. When this reaction was performed on **6**, using a sufficiently lipophilic solvent (10% H_2O in THF), additional crosslinking in the core of the siloxane elastomer resulted: the THF allowed the

transport of water to the interior of the elastomers, and removal of the benzylamine. As the reaction progressed, small bubbles (H_2) formed on the surface of the elastomer, and ATR-FTIR of the disks after reaction revealed the absence of SiH functionality at the interior of the elastomer. Comparison of the ^{29}Si magic angle spinning solid state NMR (MAS ssNMR) spectra of the starting elastomer **3** and the cross linked product **7** showed the O_2SiHMe peak was removed by reaction with water, with a corresponding increase in the Me$SiO_{3/2}$ peak associated with formation of a new siloxane bond (**Figure 3.3**). This confirms the availability of the interior SiH bonds for reactions in appropriate solvent and confers the ability to fine tune the interior physical properties of the elastomer post-surface grafting to suit the desired application. Unlike β-allyloxynaphthalene, with appropriate choice of solvent, penetration of polar water and the relatively hydrophilic benzylamine were not apparently hindered by the presence of hydrophilic PEG at the liquid/polymer interface.

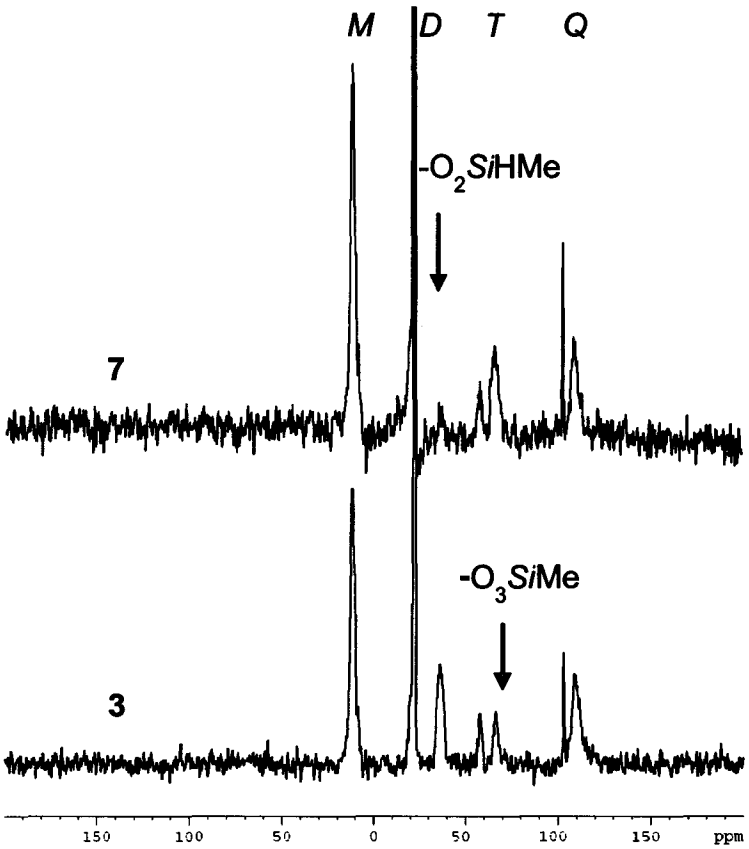


Figure 3.3: ^{29}Si MAS ssNMR of elastomers 3 and 7

Stratified silicone elastomers are available by careful manipulation of solvent conditions, taking into consideration relative solubility (or swellability) of the elastomer, and reagents. Low solubility of the reagent (e.g., PEG) directs reaction to the external interface. Similar results would be expected with the use of solvents that do not swell the silicone. For example, in water or water/methanol, reaction is directed to the external interface: acid catalyzed silicone redistribution of DC1107 was constrained to the external surface of a silicone elastomer.[6, 9] However, highly hydrophilic materials can be directed to the interior of the elastomer by use of appropriate mixed solvents that swell the

silicone and dissolve the reagent (benzylamine, water/THF). Judicious application of this principle may permit either stratification or creation of controlled gradient concentrations within the elastomer.

Manipulation of the silicone elastomer structure is further facilitated by existing 'strata'. A pre-existing PEG layer was able to reduce the efficiency of migration of allyloxynaphthalene into the interior in a good solvent for silicones (*cf.* reaction of hydrophobic **1** (complete reaction) with hydrophilic-surfaced **3** (incomplete reaction)). Thus, the PEG layer acts an inefficient filter to control access to the silicone core. The exploitation of the ability of such surfaces to control transport of reagents to the core of elastomeric silicones will be the subject of future reports.

3.4 Conclusion

The reaction locus of SiH-rich silicone elastomers can be readily controlled by solvation. Hydrophilic solvents or incompletely solvated hydrophilic reagents dispersed in hydrophobic media will preferentially undergo reaction at the external interface. Hydrophobic solvents, which effectively swell the silicone elastomer body, can also deliver reagents to the interior where various types of reactions including metal ligand reduction (Pt colloid formation), hydrosilylation and nucleophilic substitution can then occur. The combination of these approaches constitutes a generic strategy to permit the controlled assembly of

stratified silicones with hydrophilic external layers, and a variety of internal modifications, including higher levels of crosslinking .

3.5 Experimental Section

Materials

Mono-allyl poly(ethylene glycol)(550 M_W) was used as received from Clariant; benzylamine, β-naphthol, allyl bromide and Karstedt's catalyst (2% solution in xylenes) were purchased from Aldrich and used without further purification. Sylgard 184 elastomer preparation kit (comprised of two parts: vinylsilicone + catalyst "base" and SiH "curing agent" component) and poly(hydromethylsiloxane) (PHMS, DC1107) were purchased from Dow Corning, and potassium carbonate and solvents were purchased from Caledon. Solvents were dried using pressurized activated alumina columns prior to use. Solution NMR spectra were recorded using a Bruker Biospin AV200 and MAS ssNMR (solid state) were performed on a Bruker AV500 spectrometer. Infrared spectra were recorded on a Bio-Rad FTS-40 attenuated total reflection Fourier transform IR using a horizontal cadmium selenide ATR apparatus.

Synthesis of SiH elastomer 1

In a typical synthesis, Sylgard 184 base (10 g), DC1107 (1 g), and Sylgard 184 curing agent (1 g) were combined in a beaker, and the mixture was manually stirred for 30 s before transfer to a 100 x 15mm Petri dish. The Petri dish was leveled within a vacuum desiccator and the elastomer mix was degassed under

vacuum. The surfaces were left to cure under vacuum for 24 h, ultimately to provide a hydrosilane functional elastomer film of approximately 2 mm thickness. Disks were cut from the film using a 7mm diameter circular punch, producing roughly 80 elastomer disks per Petri dish. These disks were added to a vial and dry hexanes (9mL) was added, and stirred for 6h to remove any unbound silicones from the elastomer. The SiH disks were shaken repeatedly with dry hexanes and placed under vacuum to remove residual solvent, then stored until use in a desiccator over Drierite.

ATR-FTIR (cm^{-1}) = 2962 (Si-CH_3); 2166 (SiH).

Synthesis of SiH-core PEG-surfaced PDMS elastomer 3

In a typical experiment, 10 SiH disks **1**, 550MW mono-allyl PEG (1.00 mL, 1.80 mmol), and Karstedt's catalyst (20 µL, 2% solution in xylenes) were mixed in hexanes (3.0 mL) and stirred at room temperature for 6 h. After the reaction period, the disks were shaken repeatedly with dichloromethane (2 x 5 mL), ethanol (2 x 5 mL) and water (2. x 5 mL) and dried under vacuum for 6 h. The disks were stored in a desiccator over Drierite. Control samples were prepared in the same manner but without catalyst.

^{29}Si ssNMR δ = 12 ($SiOR_3$), -21 (SiO_2R_2), -38 (SiO_2R_2), -68 (SiO_3R), -105 (rotor), -112 (SiO_4). ATR-FTIR (cm^{-1}) = 2962 (-CH_3); 2873 (-CH_2-); 2166 (SiH).

Synthesis of β-allyloxynaphthalene

β-Naphthol (8.8322g, 61.33mmol) and allyl bromide (8.0 g, 66.0 mmol) were mixed in 200 mL acetone and refluxed for 1.5 h in the presence of K_2CO_3

(34.48 g, 249.48 mmol). The extent of the reaction was followed by TLC using a 4:1 hexanes-ethyl acetate eluent. The reaction mixture was filtered and the solvent removed under vacuum. The crude product was purified using flash chromatography on dry loaded silica with 10:1 hexanes-diethyl ether as eluent, affording the desired product as a yellow oil (6.2384g, 33.904mmol, 57% yield).

^{1}H-NMR ($CDCl_3$) δ = 7.500 (m, 7H); 6.106 (m, 1H); 5.487 (d, 1H, 8.6Hz); 5.382 (d, 1H, 3.7Hz); 4.670 (d, 2H, 2.6Hz).

Synthesis of naphthyl modified elastomer 2

In a typical experiment, 10 elastomer discs **1** (SiH throughout) were swollen in a solution of β-allyloxynaphthalene (1.0 mL, 6.1 mmol) in toluene (3.0 ml, 28.2 mmol) for 6 h. Karstedt's catalyst (20 µL, 2% solution in xylenes) was added and the mixture was shaken overnight (~18 h). After the reaction, the discs were extracted with dichloromethane in a Soxhlet apparatus for 24 h. The discs were dried with N_2 and then under vacuum for 5 h, producing transparent elastomers with a golden yellow color.

ATR-FTIR (cm^{-1}) = 2962 ($-CH_3$), 1630 (C=C), 1600 (C=C)

^{13}C MAS ssNMR δ = 129.2, 127.6, 126.8, 119.0, 106.4, 41.2, 40.8, 39.7, 25.5, 23.0, 13.5, 11.3, 8.35, 3.8, 3.4, 1.8, 1.6, 1.1, 0.6, 0.2, -0.3, -2.6

Synthesis of PEG surface, naphthyl core-modified elastomer 4

In a typical experiment, 10 elastomer disks **3** (PEG surface with SiH core) were swollen in a solution of β-allyloxynaphthalene (1.0 mL, 6.1mmol) in toluene (3.0 mL) for 6 h. Karstedt's catalyst (20µL, 2% solution in xylenes) was added

and the mixture was stirred for a further 6 h. After reaction, disks were extracted with dichloromethane in a Soxhlet apparatus for 12 h, and dried under vacuum for 6 h, producing transparent elastomers with a golden yellow color.

ATR-FTIR (cm^{-1}) = 2962 ($-CH_3$), 2166 (SiH), 1630 (C=C), 1600 (C=C).

^{13}C MAS ssNMR δ = 139.2, 132.2, 129..5, 127.4, 122.1, 119.4, 107.8, 80.4, 73.1, 71.2, 61.5, 29.7, 25.5, 22.3, 9.6, 0.8, 0.6, 0.5, 0.2, -0.3, -0.9

Core SiH activation of 3 with benzylamine to give elastomer 6

In a typical experiment, 10 elastomer disks **3** (PEG surface with SiH core) were swollen in a solution of benzylamine (1.0 mL, 9.1mmol) and toluene (3.0 mL) for 6 h. The disks changed color from transparent to white upon swelling. The disks were washed thoroughly with dry toluene and dried under vacuum for 6 h. The disks were stored in a desiccator over Drierite.

ATR-FTIR (cm^{-1}) = 3292 ($-NH_2$), ^1H-NMR δ = 7.29 (m, 5H, 15Hz, -Ph); 3.88 (s, 2H, $-CH_2-$); 1.42 (s, 2H, $-NH_2$),

Post-graft crosslinking of 6 to give elastomer 7

In a typical experiment, 10 benzylamine activated PEG/SiH elastomer disks **6** were swollen in a solution of 10% water in THF (3 mL) for 1 hour, during which time bubbles formed at the surface of the elastomer. After reaction, the disks were successively washed with toluene, and then dried under vacuum for 6 h. Additional crosslinking was evident from ssNMR. Control experiments with non-activated SiH disks did not lead to changes in crosslink density during the same time of reaction.

^{29}Si MAS ssNMR δ = 12 (R_3SiO), -21 (R_2SiO_2), -68 ($RSiO_3$), -105 (rotor), -112 (SiO_4)‡, ATR-FTIR (cm^{-1}) = 2962 ($-CH_3$)

Formation of Pt colloids within an elastomer matrix 5

In a typical experiment, 10 PEG-outer modified disks **3** were stirred in dry toluene (3mL) for 6 h, and then Karstedt's catalyst was added (50μL, 2% solution in xylenes). The disks were washed thoroughly with dry toluene and dried under vacuum for 6 h. The resulting disks were dark brown in color. The disks were stored in a desiccator over Drierite.

ATR-FTIR cm^{-1} = 2962 ($-CH_3$), 2166 (SiH).

3.6 Acknowledgements

The authors thank the Natural Sciences and Engineering Research council for funding, Clariant for the gift of mono-allyl poly(ethylene oxide), Dr. Lindsay Cahill and Dr. Bob Berno for assistance with solid state NMR experiments and Hélène Jochem for assistance with preparation of starting materials.

‡ Sylgard 184 contains 10 – 30% Me_3Si-modified hydrophobic silica as a reinforcing agent.

3.7 Supplementary Information

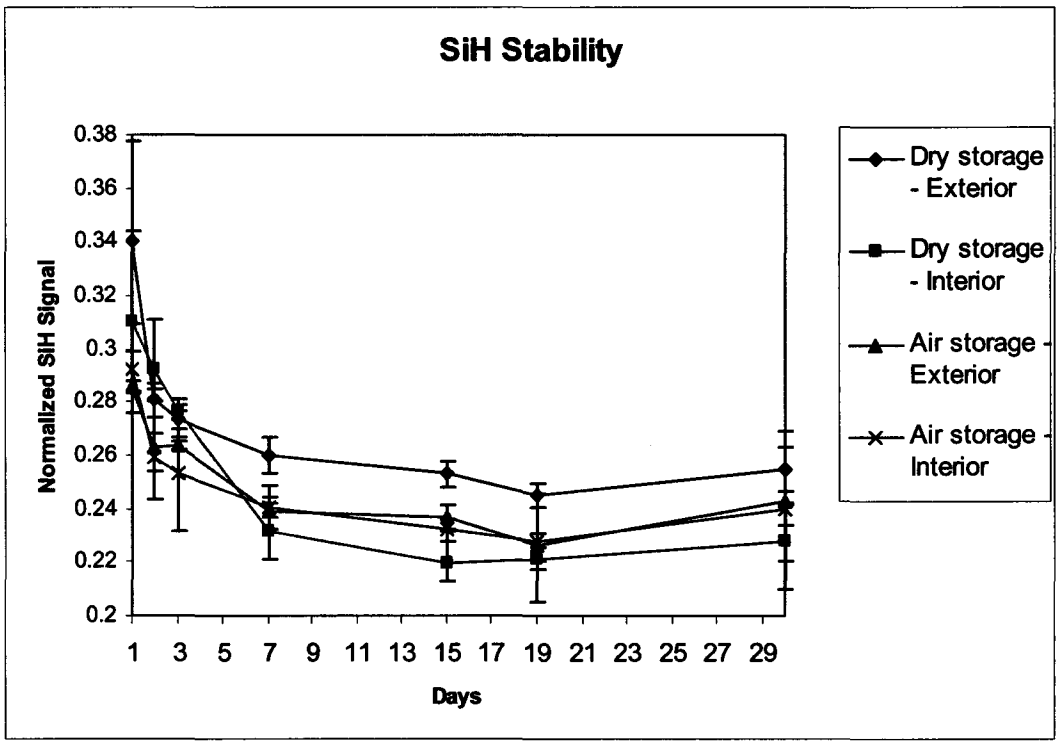


Figure 3.4: Normalized SiH signal intensity by ATR-FTIR for the interior and exterior of disks stored under dry and ambient conditions.

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Chapter 4: Hydrolytically Stable Linkers for Silicone Carbohydrates Derived from Hydrodiisopropyslilanes[§]

David B. Thompson, Ferdinand Gonzaga, Amanda S. Fawcett and Michael A. Brook

4.1 Abstract

Two strategies were developed for the attachment of sugars to siloxanes using bifunctional silicon linkers: the substrate could be functionalized with a silyl hydride before coupling to a vinyl-terminated siloxane through platinum catalyzed hydrosilylation; alternatively, unprotected glucose could be directly silylated by a silicone terminated with a chlorosilyl group. Optimal steric bulk was found with difunctional diisopropylsilanes, which exhibit excellent reactivity for preparation of sugar silane derivatives, and also permit efficient grafting to silicones via hydrosilylation. The resulting product alkoxysilane-silicone exhibits greater stability to hydrolysis than the silicone itself.

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4.2 Introduction

One of the most attractive aspects of silicone polymers is their tractability, which allows for ready chemical modification: such structural manipulation is necessary, in some cases, to obtain desirable properties. For example, the high hydrophobicity of silicone materials can be attenuated by covalent linkage to hydrophilic moieties. Polymers such as poly(ethylene oxide) (PEO) are commonly used for this purpose, and the resulting amphiphiles frequently take the form of block or brush co-polymers. These materials have found widespread application as surfactants, foam stabilizers, defoaming agents and 'super-wetters'.[1-3]

Saccharides exhibit interesting properties that range from the ability to participate in explicit biological recognition events with low molecular weight materials, to structural supports with high molecular weight materials. They are intriguing hydrophilic starting materials because of their abundance and availability as a variety of complex structures. We and others are interested in developing strategies to combine the unusual features of silicones with those of carbohydrates. The resulting amphiphilic polymers may be expected to possess interesting surface activities and biocompatibility.[4]

Two strategies may be considered for binding silicones to saccharides: Si-O-sugar or Si-C-O-sugar linkages. The latter strategy is almost universally adopted in the literature, as the linkage is stable to hydrolysis under normal

conditions. Synthesis of the ligand requires that the carbohydrate is first provided with a carbon-carbon π-bond (e.g., allyl, propargyl) typically using an ether or ester tether, either before or after protection of remaining free hydroxyl groups.[5, 6] The resulting product is then hydrosilylated by hydride functional poly(dimethylsiloxanes) to form the desired composite. More sophisticated linkages can also be used, as shown in a series of papers by Wagner *et al.*[7-10] Alternative strategies utilize traditional organic chemistry on organically modified silicones, including amidation with aminoalkyl functional silicones,[11] esterification of carbohydrates with acid functional siloxanes,[12] acetalization of aldehyde-functional silicones to glucose through an acetal group,[13, 14] and the use of enzymes to graft from carbohydrates linked in a conventional manner.[6]

The hydrophobization of saccharides with $SiMe_3$ groups, to increase their volatility for mass spectrometry experiments was one of the early examples of silyl protecting groups.[15] However, the use of silyl ethers to directly link silicone polymers to carbohydrates is not generally useful, as the hydrolytic stability of such alkoxysilanes, OMe_2SiO-*C*, is low (*cf.* Me_3Si [16, 17]). Synthetic organic chemists routinely overcome this limitation in hydrolytic stability by blocking/protecting alcohols with silyl ethers of much higher steric bulk: the ease of introduction and deprotection of the silyl group are both tied in a predictable manner to the degree of steric encumbrance at silicon. The strategy has been broadly applied to a wide variety of functional groups[18-20] including carbohydrates.[21] We were interested in taking advantage of established rules for

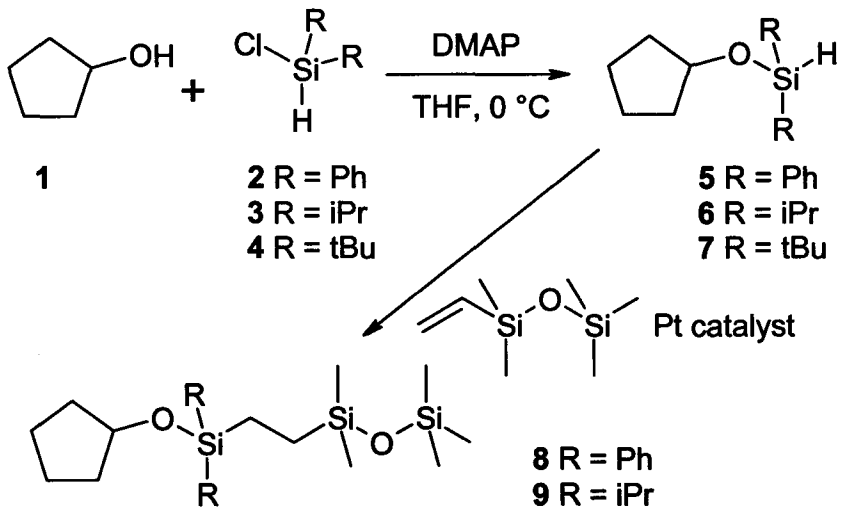
protecting group stability, and developing suitable linkers to prepare carbohydrate modified silicones using *Si*-*O*-C-Sugar linkages.

To design an effective silyl ether linkage, it is necessary to control multiple reactivities at a single silicon center.[20] We decided that the most generic strategy would utilize a silane that has two functional groups with orthogonal reactivity, a good leaving group that can bind to the sugar alcohol using nucleophilic substitution, and a hydrosilane, that can graft to silicones using well established hydrosilylation processes. Since both the desired synthetic reactions (alcohol silylation, hydrosilylation) and the undesired hydrolytic decomposition processes (silyl ether and silyl hydride solvolysis) are governed primarily by the steric environment at silicon,[16] an increase in stability for the product silyl ether will come at the cost of reduced rate of its formation. It was thus necessary to develop a silyl group that is sufficiently reactive to allow its introduction to the OH group by nucleophilic substitution, also to permit reaction of the SiH group with olefins, and yet be stable to subsequent hydrolysis. We describe below our finding that diisopropylsilanes provide the optimal balance of orthogonal reactivity that allows ready formation of silicone carbohydrates through a Si-O-C-sugar linkages, but for which the product silyl ether is *more stable* to hydrolysis than silicones themselves.

4.3 Results and Discussion

4.3.1 Model compounds

Cyclopentanol **1** was used as a model compound to establish the optimal steric bulk at silicon and in order to simplify spectral interpretation. Cyclopentanol reacted quickly with commercially available chlorodiphenylsilane **2**, chlorodi*iso*propylsilane **3** and chlorodi*tert*butylsilane **4** to cleanly produce model compounds diphenyl **5**, diisopropyl **6** and ditbutyl **7** cyclopentoxysilanes, respectively. Even the bulky *t*-butyl compound formed in less than 1 hour in THF at 0 °C in the presence of one equivalent of DMAP (Scheme 4.1).



Scheme 4.1: Synthesis of Model Compounds

The rate of hydrosilylation of **5-7** correlated directly with the steric environment at silicon. The steric bulk of **7** reduced the reactivity of the silyl hydride below acceptable levels; even after heating for several days at

temperatures of 120 °C, less than 5% of the desired product was produced (by ^{1}H NMR). Compound **5** reacted with vinylpentamethyldisiloxane in the presence of Karstedt's platinum complex (2% solution in xylenes; for a crystal structure of $Pt_2(H_2=CHSiMe_2OSiMe_2CH=CH_2)_3$ see [22]) to form **8**, requiring 48 hours at 65 °C to reach completion, though with some contamination (see stability data), while **6**, by comparison, required 48 hours in refluxing toluene to complete the corresponding reaction to form **9** (Scheme 4.1). Thus, both elements of the linking reaction work effectively, C-O-Si formation and hydrosilylation.

The utility of this approach to prepare silicone carbohydrates depends upon reliable and predictable hydrolytic stability of the Si-O-C linkage, and of the functional silyl hydride. The susceptibility of model compounds **5**, **6** and **7** towards solvolysis was studied in hydrated CD_3OD. The rate of cleavage of the silyl ethers was established by integration of the ^{1}H NMR signals for the proton at C1 of cyclopentanol and the silyl hydrides. While all three compounds were cleaved within 72 hours (Figure 4.1), steric effects manifested themselves as expected. After 24 hours, 68% of the silyl ether of **7** had cleaved, compared to 73% for **6**, and 82% for **5**.

The diphenyl compound **5** was also found to spontaneously decompose in the presence of atmospheric water over the course of weeks to months, depending on humidity. Additionally, compound **5** partly decomposed during hydrosilylation, contaminating samples of **8** and complicating stability assays. By contrast, **8** itself showed no appreciable decomposition under the conditions and

timeframe used for the model compounds. A key finding for the utility of these compounds is that the stability of the Si-H bond was found to exceed that of the corresponding silyl ether (Si-O-C) bond for all model compounds. After 240 hours, the total Si-H signals accounted for 61% (**5**), 81% (**6**) and 98% (**7**), respectively, of the starting materials.

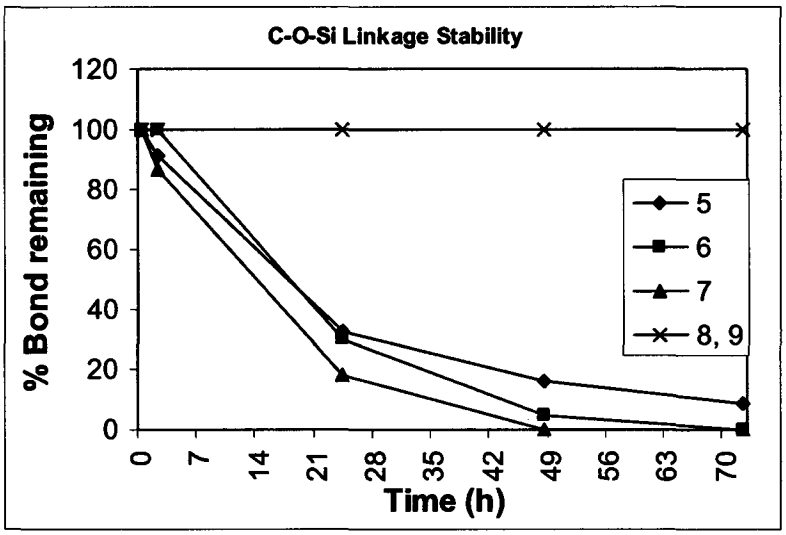
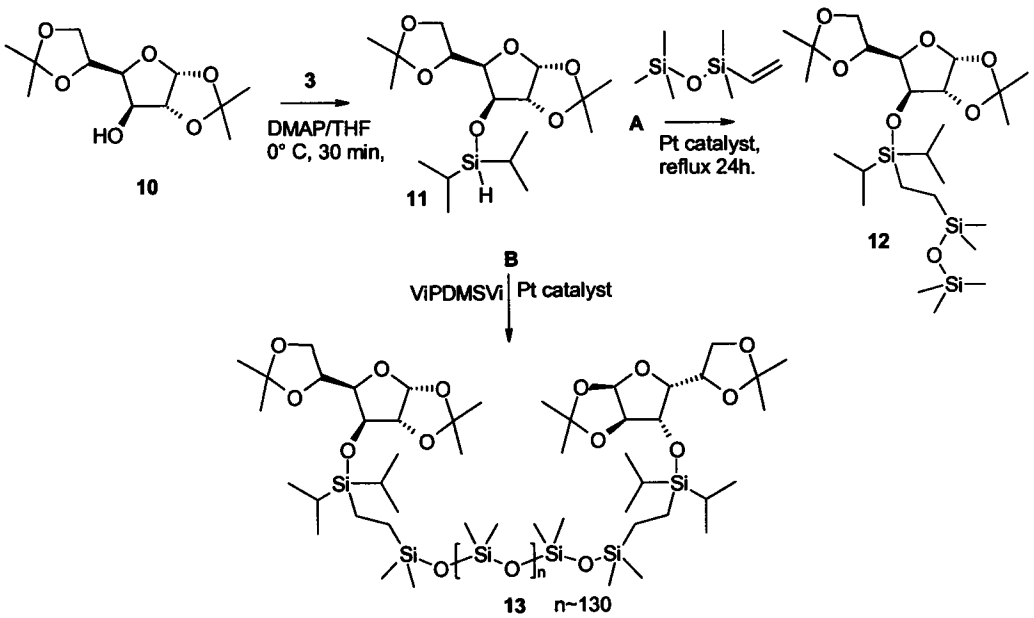


Figure 4.1: Stability of Silyl Ethers (see experimental for conditions)

4.3.2 Protected Saccharide

Compound **6**, the diisopropylsilyl compound, exhibited the best balance between ease of preparation, stability to solvolysis, and reactivity towards hydrosilylation. Therefore, the model saccharide 1,2,5,6-di-O-isopropylidene-α-D-glucofuranose (diacetone glucose, **10**) was reacted with **3** to afford, after column chromatography, hydrosilane **11** in 89% yield. The saccharide, somewhat surprisingly given the number of functional groups present, was significantly more robust than the model compound **6**, showing only ~10% silyl ether cleavage

after 24 hours in CD_3OD/D_2O. Compound **11** was successfully hydrosilylated onto 1-vinyl-1,1,3,3,3-pentamethyldisiloxane to give sugar-siloxane **12** in 79% yield (Scheme 4.2A), or onto bis-vinyl-terminated polydimethylsiloxane (MW 6000) to give **13** in 75% yield (Scheme 4.2B).



Scheme 4.2: Linkage of sugar silane 11 to short (A) and long (B) siloxanes

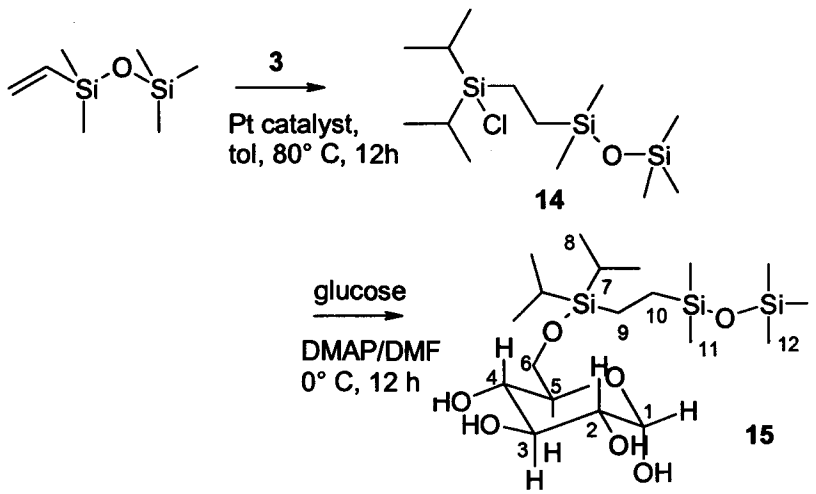
Silicones readily depolymerize under basic or acidic conditions, a property used to establish that the hindered C-O-Si linkage in **12** was at least as stable as the attached siloxane. The same hydrolysis conditions as above (CD_3OD/D_2O) were applied, but with the addition of CD_3COOD (150 µL) to provide additional solvolytic stress to the siloxane linkage. After 45 hours, new signals in the ^1H NMR had appeared in the methylsiloxane region, with the original signal retaining only 62% of its initial intensity. However, no new signals were observed for the

isopropyl-silane or the carbohydrate protons. This clearly shows that the stability of the hindered silyl ether linkage towards acidic hydrolysis exceeds that of the methylsiloxane to which it is attached. This demonstrates that hindered alkoxy-diisopropylsilane groups are viable and convenient linkers for silicones to alcohol-based polymers including carbohydrates: the alkoxysilane is more stable than the silicone constituent in such copolymers (Scheme 2).

4.3.3 Unprotected Saccharide

The order in which the two reactivities of **3** are utilized is at the discretion of the experimentalist. As shown above, by silylating a protected saccharide, great control can be exercised over the location of attachment. This control is limited only by the well developed rules of carbohydrate protection. Since chlorosilanes are unaffected by platinum catalyzed hydrosilylation, it is also possible to hydrosilylate the functional group onto a siloxane first, in effect creating a silicone protecting group. This was demonstrated by reacting **3** with pentamethyldisiloxane to create chlorosiloxane **14**. This compound reacted directly with glucose in DMF to produce unprotected sugar-siloxane **15** (Scheme 4.3). A ^{1}H-^{29}Si heteronuclear multiple bond correlation (HMBC) NMR experiment confirmed that the reaction occurred primarily (>85%) at the primary C6 position, with the remaining product consisting of silylation at secondary centres. The stability to CD_3OD/D_2O was also examined for this compound. Anomerization of the sugar was observed, and at the same time a white precipitate appeared in

solution, ascribed to cleavage of the minor fraction of product silylated at the anomeric position (<3%). After 120 hours, this solid was removed through filtration. NMR showed the remaining product remained stable in solution, and no further precipitate or other reaction was observed, even after several weeks.



Scheme 4.3: Synthesis of unprotected sugar-siloxane 15

As noted above, either before or after making a diisopropylsilyl ether, the hydrosilane efficiently undergoes platinum catalyzed hydrosilylation. That is, the steric compression exerted by the isopropyl groups is more effective at controlling reactivity of the Si-O linkage, than at the SiH linkage. Subtle steric effects, which can be manifested in change in hydrosilylation regiochemistry, are well known within platinum ligand spheres during hydrosilylation.[23] Diisopropylsilanes, with various combinations of functional groups, are readily available. The ability of these groups to balance reactivity for hydrosilylation, yet

stability to hydrolysis, has the potential to be exploited in linking a variety of disparate materials, which will be the subject of future reports.

4.4 Conclusions

Functional hydridosilanes of varying steric encumbrance were developed for the attachment of carbohydrates to siloxanes. Through the use of a cyclopentanol model, the steric environment of diisopropylsilanes was determined to provide the best balance of reactivity through alcohol silylation and hydrosilylation, which permits introduction of the silicone, and stability of the product silicone-carbohydrate ether towards hydrolysis. This linkage was used to bind a siloxane to either protected or unprotected saccharides. The hindered C-O-Si linkage was shown to have greater solvolytic stability in weak acid than a dimethylsiloxane, such that the strategy can be used with silicone polymers.

4.5 Experimental Section

General Methods

Diacetone glucose, DMAP, cyclopentanol and DMF were purchased from Aldrich and all silicon containing compounds, as well as Karstedt's solution (2% in xylenes), were purchased from Gelest. Deuterated solvents were purchased from Cambridge isotopes. Solvents (other than DMF) were purchased from

Caledon and dried using pressurized alumina columns. α-D-glucose was purchased from Aldrich and was heated in vacuo to remove residual water.

NMR spectra were recorded using Bruker Biospin AV200, AV600 and DRX500 spectrometers. Infrared spectra were recorded on a Bio-Rad FTS-40 Fourier transform IR. CI-MS were performed on a Micromass GCT. High resolution ESI-MS spectra were recorded on a Micromass Global Q-TOF Ultima.

General synthesis of model hydrosilanes

In a typical silylation, dimethylaminopyridine (2.277 g; 18.63 mmol) was dissolved in THF (20 mL) under a nitrogen atmosphere with stirring. Cyclopentanol (1.613 g; 18.72 mmol) was added dropwise via syringe. The resulting solution was cooled with an ice/water bath before addition of an equimolar amount of the desired dialkylhydrochlorosilane dropwise via syringe. A white precipitate formed immediately upon addition of the chlorosilane. The resulting mixture was stirred at reduced temperature for 30 min. Pentanes (30 mL) were added to the reaction crude, which was filtered over a Celite pad and concentrated on a rotary evaporator, resulting in a colourless oil. This was distilled at reduced pressure (1 mmHg) to afford the desired product in 63-75% yield.

Spectral Data

Cyclopentoxydiphenylsilane (**5**) – 72%:

^{1}H NMR ($CDCl_3$) δ = 7.65 (m, 4H); 7.42 (m, 6H), 5.45 (s, 1H, SiH); 4.44 (m, 1H), 1.61 (m, 8H); ^{13}C NMR ($CDCl_3$) δ = 134.8, 133.9, 130.3, 128.1, 76.7, 35.3, 23.2; FTIR (neat) cm^{-1} = 2118.5 (SiH); MS (TOF, Cl^+): m/z = 268 (8%) [M^+], 199 (44%) [M – Cpy^+], 190 (66%) [M – Ph^+], 183 (62%) [M – $CpyO^+$].

Cyclopentoxydi*iso*propylsilane (**6**) – 75%:

^{1}H NMR ($CDCl_3$) δ = 4.27 (m, broad, 1H); 4.13 (s, 1H, SiH), 1.60 (m, broad, 8H), 1.01 (s, 14H); ^{13}C NMR ($CDCl_3$) δ = 76.3 (hidden beneath $CDCl_3$ peak), 35.4, 23.2, 17.6, 17.5, 12.6; FTIR (neat) cm^{-1} = 2088 (SiH); MS (TOF, Cl^+) m/z: 200 (37%) [M^+], 157 (94%) [M – iPr^+].

Cyclopentoxydi*tert*butylsilane (**7**) – 63%:

^{1}H NMR ($CDCl_3$) δ = 4.32 (m, broad, 1H); 3.99 (s, 1H, SiH); 1.60 (m, broad, 8H), 0.98 (s, broad, 14H); ^{13}C NMR ($CDCl_3$) δ = 77.9, 35.3, 27.5, 23.1, 20.3; FTIR (neat) cm^{-1} = 2084.3 (SiH); MS (TOF, Cl^+): m/z = 228 (13%) $[M]^+$, 171 (75%) [M – $tBu]^+$.

Hydrosilylation protocol

In a typical hydrosilylation, the desired model compound (0.25 g) was dissolved in dry toluene (5 mL) to which vinylpentamethyldisiloxane (~3.5 molar equiv.) was added, followed by a single drop of Karstedt's catalyst (2% solution in xylenes). The reaction mixture was heated to the desired temperature (65 °C for **5** and reflux for **6**) and left for 48 hours. The crude product was diluted in ethyl

acetate (15 mL) and stirred overnight with activated charcoal. The resulting mixture was filtered over a Celite pad and concentrated on a rotary evaporator.

Spectral Data:

Diphenyl compound (**8**) – 87%:

^{1}H NMR ($CDCl_3$) δ = 7.59 (m, 4H); 7.36 (m, 6H), 4.34 (m, 1H); 1.75 (m, 8H); 1.07 (m, 2H); 0.54 (m, 2H); 0.05 (s, 9H); 0.02 (s, 6H); ^{13}C NMR ($CDCl_3$) δ = 142.8, 141.6, 136.4, 134.5, 81.9, 42.4, 30.0, 16.3, 12.2, 8.8, 6.5.

Di*iso*propyl compound (**9**) – 60%:

^{1}H NMR ($CDCl_3$) δ = 4.27 (m, 1H); 1.59 (m, 8H); 1.06 (s, broad, 14H); 0.53 (m, 4H); 0.07 (s, 9H); 0.05 (s, 6H); ^{13}C NMR ($CDCl_3$) δ = 74.5, 36.1, 23.4, 17.9, 17.0, 12.5, 9.9, 2.1, -0.3

General procedure for stability measurements

In a typical experiment, ~30 mg of test compound was dissolved in CD_3OD (1 g), to which D_2O (50 μL) was added, and the resulting solution was left in a sealed NMR tube at room temperature. The proton NMR of this mixture was taken over time, and integration of the proton at position 1 of the cyclopentoxy ring was used to evaluate rate of silyl ether cleavage. For the stability measurements of protected sugar siloxane **12** the procedure was as above, but with the addition of CD_3COOD (150 μL). The integration of methylsiloxane protons was used to evaluate the stability of the non-hindered siloxane bond.

Synthesis of 3-diisopropylhydrosilane-1,2,5,6-di-O-isopropylidene-α-d-glucofuranose 11

Diacetone glucose (2.0063 g, 7.68 mmol) and 4-dimethylaminopyridine (1.0322 g, 8.45 mmol) were combined in a dry flask with a stir bar under a nitrogen atmosphere. Dry THF (50 mL) was added and the flask was cooled with an ice/water bath before adding diisopropylchlorosilane (1.2912 g, 8.56 mmol) drop wise via syringe. A white solid precipitated immediately, and the resulting mixture stirred for 1 h. The white solid was removed via filtration and the solvent was removed with rotary evaporation, affording a clear oil. The crude product was chromatographed on silica (5:1 hexanes/ethyl acetate eluant) to give diacetoneglucosyldiisopropylsilane as a colourless oil (2.561 g, 89% yield).
FT-IR (neat): 2939; 2096 (Si-H), 1073 cm^{-1} (Si-O-C); ^{1}H NMR ($CDCl_3$) δ = 5.88 (d, 1H, *J* = 3.6 Hz), 4.44 (d, 1H, *J* = 3.6 Hz), 4.30 (d, 1H, *J* = 2.4 Hz), 4.27 (s, 1H), 4.27 (m, 1H), 4.10 (dd, 1H, *J* = 8.4, 6.6 Hz) 4.07 (dd, 1H, *J* = 7.8, 3.0 Hz) 3.97 (dd, 1H, *J* = 8.4, 6.0 Hz), 1.50 (s, 3H), 1.41 (s, 3H), 1.33 (s, 3H) 1.32 (s, 3H), 1.06 (d, 6H, *J* = 2.4 Hz) 1.04 (d, 6H , *J* = 2.4 Hz); ^{13}C NMR ($CDCl_3$) δ = 111.4, 108.5, 84.5, 81.7, 71.8, 67.1, 26.5, 26.3, 25.8, 24.8, 17.2, 16.9, 16.8, 16.5, 12.0, 11.6; ^{29}Si NMR ($CDCl_3$) δ = 15.62 ppm; HRMS (ESI) calculated for $C_{18}H_{38}NO_6Si^+$ $[M+NH_4^+]$ = 392.2468, found 392.2473.

Synthesis of 3-(1-disopropylsilyl-2-pentamethyldisiloxyethyl)-1,2,5,6-di-O-isopropylidene-α-D-glucofuranose 12

Diacetoneglucosedi*iso*propylsilane (0.4965 g, 1.32 mmol) was combined with vinylpentamethyldisiloxane (2.001 g, 11.5 mmol) in a flask with a stir bar and equipped with a water-jacket condenser. The reaction mixture was heated to reflux for 48 h, after which the condenser was turned off to allow excess disiloxane to evaporate. The crude reaction mixture was diluted with hexanes, and then stirred over activated charcoal for 30 min. The resulting mixture was filtered and concentrated on a rotary evaporator, affording protected glucose-disiloxane at >95% purity by proton NMR (0.5761 g, 1.05 mmol, 79% yield). ^{1}H NMR ($CDCl_3$) δ = 5.85 (d, 1H, *J*=3.4 Hz), 4.36 (d, 1H, *J*=3.4 Hz), 4.28 (m, 2H), 4.04 (m, 3H), 1.48 (s, 3H), 1.39 (s, 3H), 1.31 (s, 3H), 1.30 (s, 3H) 1.05 (s, broad, 14H), 0.56 (m, complex, 4H), 0.06 (s, 9H), 0.05 (s, 6H); ^{13}C NMR ($CDCl_3$) δ = 111.9, 109.1, 105.3, 85.8, 82.5, 75.8, 72.2, 67.7, 27.1, 26.9, 26.5, 25.5, 17.8, 12.5, 12.4, 9.9, 2.1, -0.3; ^{29}Si NMR ($CDCl_3$) δ 17.81, 7.84, 7.45; FT-IR (neat): 2955; 1050 (Si-O-Si); 1070 cm^{-1} (Si-O-C); HRMS (ESI) calculated for $C_{25}H_{56}NO_7Si_3^+$ $[M+NH_4]^+$ = 566.3365, found 566.3347.

Synthesis of 1,2,5,6-di-O-isopropylidene-α-D-glucofuranose terminated poly(dimethyl)siloxane 13

Diacetoneglucosedi*iso*propylsilane (0.2635 g, 0.704 mmol) was combined with 6000 MW vinyl terminated poly(dimethyl)siloxane (1.0068 g, 0.168 mmol), toluene (dry, 3mL) and 3 drops of Karstedt's catalyst (2% solution in xylenes) in a flask with a stir bar and equipped with a water-jacket condenser. The reaction

was heated to reflux for 24 h. The crude reaction mixture was diluted with dichloromethane, and then stirred with activated charcoal for 4 h. The resulting mixture was filtered over Celite on a silica pad, removing the charcoal as well as excess **11**. This was concentrated on a rotary evaporator affording pure product (0.8481 g, 0.126 mmol, 75% yield).

^{1}H NMR ($CDCl_3$) δ = 5.87 (d, 1H, *J*=3.8 Hz), 4.31 (m, 3H), 4.04 (m, 3H), 1.49 (s, 3H), 1.40 (s, 3H), 1.32 (s, 3H), 1.30 (s, 3H), 1.05 (s, broad, 14H), 0.53 (m, 4H), 0.08 (m, 341H); ^{13}C NMR ($CDCl_3$) δ = 111.9, 109.1, 105.3, 85.8, 82.5, 75.9, 72.2, 67.8, 29.9, 27.1, 26.9, 26.5, 25.5, 17.9, 12.4, 9.8, 1.2, -0.3; ^{29}Si NMR ($CDCl_3$) δ = 17.63, 7.78, -21.97; FT-IR (neat): 2961; 1070 (Si-O-C) ; 1050 cm^{-1} (Si-O-Si).

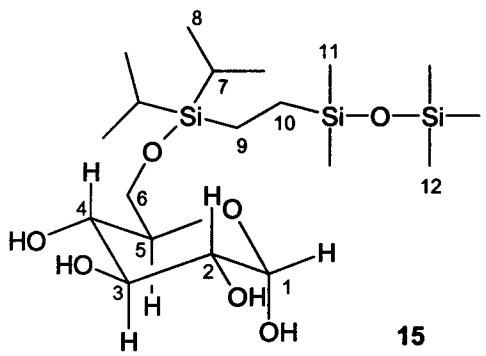
Synthesis of Chlorosilane 14

Diisopropylchlorosilane (1.05g, 7.0 mmol) was dissolved in 10 mL of dry toluene in a 25mL round-bottom flask. Vinylpentamethyldisiloxane (1.59g, 9.1mmol) was added, followed by Karstedt's catalyst (10μL; 2% solution in xylenes). The reaction mixture was stirred at 80 °C under nitrogen overnight. After cooling, 15mL of dry dichloromethane were added, and the solution was filtered through a short pad of previously dried Celite. Volatiles were removed *in vacuo* to afford the title compound as a clear, mobile oil (2.20g, 97%). Purity was checked by proton and carbon NMR, and this compound was directly used for the next step.

^{1}H NMR ($CDCl_3$): δ = 1.09 (m, broad, 14H), 0.76 (m, 2H), 0.48 (m, 2H), 0.06 (s, 9H), 0.05 (s, 6H); ^{13}C NMR ($CDCl_3$): δ 0.3, 2.7, 5.1, 10.7, 14.4, 18.0.

Synthesis of Sugar-siloxane 15

To an α-D-glucose (1.22g, 6.76 mmol) solution in dry DMF (25 mL), was added DMAP (0.43g, 3.55 mmol). The mixture was cooled in an ice bath. Then, under stirring, chlorosiloxane **14** (1.10g, 3.38 mmol) in 3 mL of dry THF was slowly added. The ice bath was then removed, and the reaction mixture was stirred under nitrogen overnight. Solvents were removed *in vacuo*, and the residue was dissolved in 80mL of a 9:1 (v:v) dichloromethane : methanol mixture. Excess glucose was then removed by filtration. The filtrate was evaporated, and the residue treated with 80 mL of acetone. The filtrate was evaporated, and the residual viscous clear oil was chromatographed over silica gel eluting with dichloromethane: methanol (7:1; v:v) to yield 1.056 g (67%) of monosilylated glucose as a white foamy solid. Preferential silylation of the primary alcohol at C6 was apparent from the 2D NMR. HMBC- heteronuclear multiple bond correlation showed strong coupling between the signals at C-6 and the silicon bearing the isopropyl groups.



15

^{1}H NMR- (500 MHz, DMSO-d_6) – 6.13 (dd, $^{3}J_{OH1-H1}$ = 4.7 Hz, $^{4}J_{OH1-H2}$ = 0.8 Hz, 1 H, OH-1), 4.88 (dd, $^{3}J_{H1-H2}$ = 4.0 Hz, 1H, H-1), 4.68 (d, $^{3}J_{OH4-H4}$ = 5.5 Hz, 1 H, OH-4), 4.59 (d, $^{3}J_{OH3-H3}$ = 4.6 Hz, 1H, OH-3), 4.38 (d, $^{3}J_{OH2-H2}$ = 6.6 Hz, 1 H, OH-2), 3.81 (dd, $^{2}J_{H6a-H6b}$ = -10.9 Hz, $^{3}J_{H6a-H5}$ = 1.9 Hz, 1 H, H-6a), 3.69 (dd, $^{2}J_{H6a-H6b}$ = -10.9 Hz, $^{3}J_{H6b-H5}$ = 5.3 Hz, 1 H, H-6b), 3.58 (ddd, $^{3}J_{H5-H6a}$ = 1.9 Hz, $^{3}J_{H5-H6b}$ = 5.3 Hz, $^{3}J_{H5-H4}$ = 9.9 Hz, 1 H, H-5), 3.43 (ddd, $^{3}J_{H3-H2}$ = 9.1 Hz, $^{3}J_{H3-H4}$ = 4.6 Hz, $^{3}J_{H3-OH3}$ = 4.6Hz, 1H, H-3), 3.11-3.04 (m, 2H, H-2, H4), 0.99 (m, 14H, -$CH(CH_3)_2$), 0.56-0.44 (m, 4H, -CH_2CH_2-), 0.06 (s, 9H, $Si(CH_3)_3$), 0.04 (s, 6H, $Si(CH_3)_2$); ^{13}C NMR (DMSO- d_6, 125.8 MHz): δ -0.4 (C12); 1.1 (C9 or C10); 1.9 (C11); 9.4 (C9 or C10); 11.7 (C7); 17.5 (C8); 63.2 (C6); 70.1 (C4); 72.0 (C5); 72.3 (C2); 73.0 (C3); 92.2 (C1); ^{29}Si NMR (from ^{1}H-^{29}Si HMBC) δ 14.53 (Si*i*Pr_2), 8.43 ($SiMe_2$), 7.19 ($SiMe_3$); HRMS (ESI) calculated for $C_{19}H_{48}NO_7Si_3^+$ $[M+NH_4]^+$ = 486.2730, found 486.2739

4.6 Acknowledgments

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Chapter 5: Rapid Assembly of Complex 3D Siloxane Architectures**

David B. Thompson and Michael A. Brook

5.1 Abstract

Few routes to well-defined 3D silicone structures exist because of their susceptibility to depolymerization/metathesis in the presence of acids or bases. The Lewis acid $B(C_6F_5)_3$ can be employed to condense hydrosilanes with alkoxysilanes, producing siloxanes and alkanes ($R_3SiH+R'OSiR''_3 \rightarrow R_3SiOSiR''_3 + R'H$). We demonstrate that balancing the steric demands at both the hydrosilane and alkoxysilanes, and the careful control of reaction conditions, permits clean condensation reactions to occur in the absence of competing metathesis processes. The resulting linear or highly branched siloxane compounds can be rapidly and easily assembled into explicit, complex 3D silicone structures in high yield.

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5.2 Introduction

Constructing complex molecular assemblies with a high degree of precision has become a paradigm in modern macromolecular science. Advances in living polymerization (both ionic[1] and radical[2]), and the ongoing development of site specific catalysis to control polyolefin molecular architectures,[3] for example, provide the synthetic chemist the ability to control MW, stereochemistry, copolymer distribution, and 3D architecture. An important consequence of this reaction control is production of more explicit structures with narrower property ranges and higher intrinsic value. Synthetic control has been achieved with condensation polymers too, notably through elegant synthesis of dendrimers using esters, amides, acetals, etc.[4] However, the ability to control silicone architectures have been noticeably absent from these developments.

The reactivity of silicones towards strong electrophiles and nucleophiles, as well as their ability to undergo redistribution (re/depolymerization) reactions under both acidic and basic conditions considerably narrows the options available to the experimentalist attempting to make explicit 3D structures. Previous efforts have shown the ability to develop limited control over backbone stereochemistry,[5] controlled copolymer synthesis using ring-opening polymerization of mixed cyclic silicone oligomers,[6] and achieved the Herculean task of assembling a silicone dendrimer.[7, 8] However, these routes are not

generic and, because of the intervention of acidic or basic conditions in the processes, are of limited practical application.

As with other polymers, it is desirable by efficient processes to make silicones with well defined architectures that have interesting properties. For example, 3D siloxane macrostructures, such as MQ resins,†† are condensation polymers of particular interest due to their ability to structure silicone interfaces.[9, 10] These are currently made by traditional condensation chemistry, which typically gives a broad distribution of polymer structures and, therefore, of properties. We have thus explored alternate strategies to prepare complex, highly branched silicone structures.

Tris(pentafluorophenyl)borane **1** is a strong Lewis acid catalyst that has been used in a number of organic and polymerization reactions.[11] This reagent has been found to strongly activate silicon-hydrogen bonds, facilitating a number of reactions such as the silylation of alcohols[12] and hydrosilylation of carbonyls[13] and thiocarbonyls.[14] More recently, this compound has been found to catalyze the condensation of hydrosilanes with alkoxysilanes to form new siloxane bonds $Si^1H + Si^2OR \rightarrow Si^1OSi^2 + RH$.[15] Chojnowski has proposed that the reaction occurs after initial formation of borohydride and oxonium intermediates: a competing decomposition reaction of these intermediates leads to metathesis $Si^1H + Si^2OR \rightarrow Si^2H + Si^1OR$.[15] Careful selection of starting materials allows for the exclusive

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†† GE Nomenclature: M=Me_3SiO, D=(Me_2SiO), T=($MeSiO_{3/2}$), Q=($SiO_{4/2}$)

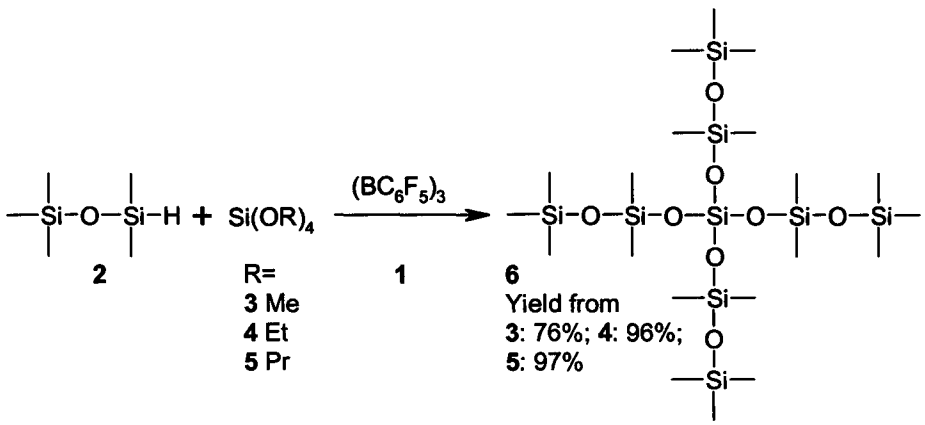
formation of a new siloxane bond with the generation of the corresponding alkane. This reaction has been used to prepare siloxane polymers in both organic solution and aqueous emulsions.[16, 17] This new synthetic method permits the formation of polydisperse linear silicone polymers, and inexplicit resins.

We report that, by manipulating the local steric environment at both alkoxy- and hydrosilane and controlling reaction conditions, it is possible to rapidly assemble complex three dimensional silicone assemblies in near quantitative yields under mild conditions; reactions can be performed in open, non-dried flasks. The use of low molecular weight starting materials allows for the easy removal of excess reagent *in vacuo*, and catalyst removal can be achieved simply by stirring with neutral alumina followed by filtration. ^{29}Si NMR showed clear chemical shift differences between M, D, T, and Q units, permitting determination of both purity and structure. While competing metathesis reactions have been reported, they were not observed in our syntheses, suggesting they can be suppressed by judicious choice of reagents and reaction conditions. These observations thus allow us to begin to articulate synthetic rules that can be applied to ensure the assembly process is governed by condensation alone.

5.3 Results and Discussion

In the reaction of pentamethyldisiloxane **2** with $Si(OR)_4$ (R= Me **3**, Et **4**, Pr **5**), the rate of reaction giving star siloxane **6** was found to inversely correlate with steric encumbrance at silicon (Scheme 5.1). This had a corresponding effect on

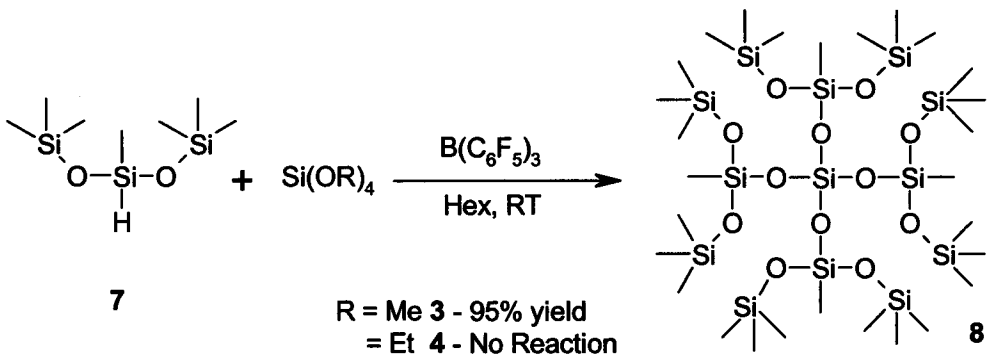
yield, most clearly seen in the transition from **3** to **4**. The more controlled, milder reaction achieved through the use of bulkier alkoxysilane **5** allowed the formation of the desired product in 97% isolated yield with no visible impurities, even in the crude material.



Scheme 5.1: Effect of steric environment on yield in synthesis of 6

The steric environment of the reacting hydrosilane is also a strong mediator in the reaction rate and selectivity. For example, 1,1,1,3,5,5,5-heptamethyltrisiloxane **7** failed to react with **4** at room temperature. However, the use of less hindered **3** with similar catalyst loadings allowed the synthesis of branched siloxane **8** in 95% isolated yield, again with no visible impurities (Figure 5.1). In order to better establish the stability and purity of these compounds, a sample of **6** was chromatographed on silica. This resulted in a 96% recovery of material with no change or degradation according to ^{29}Si NMR.

Manipulation of temperature permits the exploitation of subtle effects of steric bulk on rate. The less hindered silane **3** reacted cleanly with **7** to give **8** in excellent yield (Scheme 5.2).



Scheme 5.2: Assembly of branched siloxane 8

By contrast, the reaction of **7** with **4** did not take place at room temperature, but proceeded cleanly at 50 °C. Under these conditions, however, only three of the ethoxy groups reacted, leading to the branched mono-ethoxy compound **9** (Scheme 5.3**A**). Even in the presence of excess **7**, no evidence of **8** was observed in the silicon NMR, and **9** was isolated in 98% yield. By contrast, less sterically hindered terminal Me_2SiH groups reacted efficiently: **9** was grafted to hydrosilane terminated poly(dimethyl)siloxanes (PDMS) in order to create branch terminated silicone **10**.

The degree of control over the synthesis of structures such as **10** is necessarily limited by the polydispersity of the starting hydride functional siloxane. In order to more fully demonstrate the potential of this reaction to

construct a well-defined higher molecular weight siloxane, **9** was reacted in hexanes with phenyltris(hydridodimethylsilyloxy)silane **11** in the presence of **1** at 60 °C to form large branched siloxane **12** in 94% yield (Scheme 5.3**B**). This synthesis of an atomically precise 2600 MW symmetrical branched siloxane was achieved in two steps from commonly available starting materials in 92% overall yield. Currently, there is no other technology available to facilitate the synthesis of such complex silicone structures in a comparable manner.

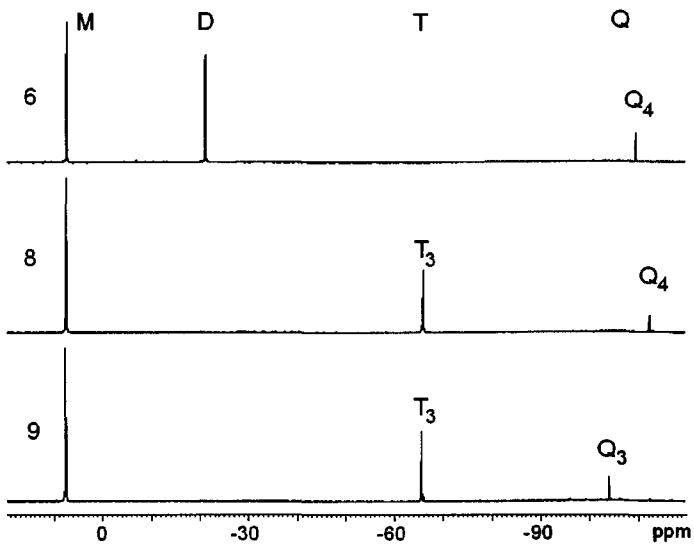
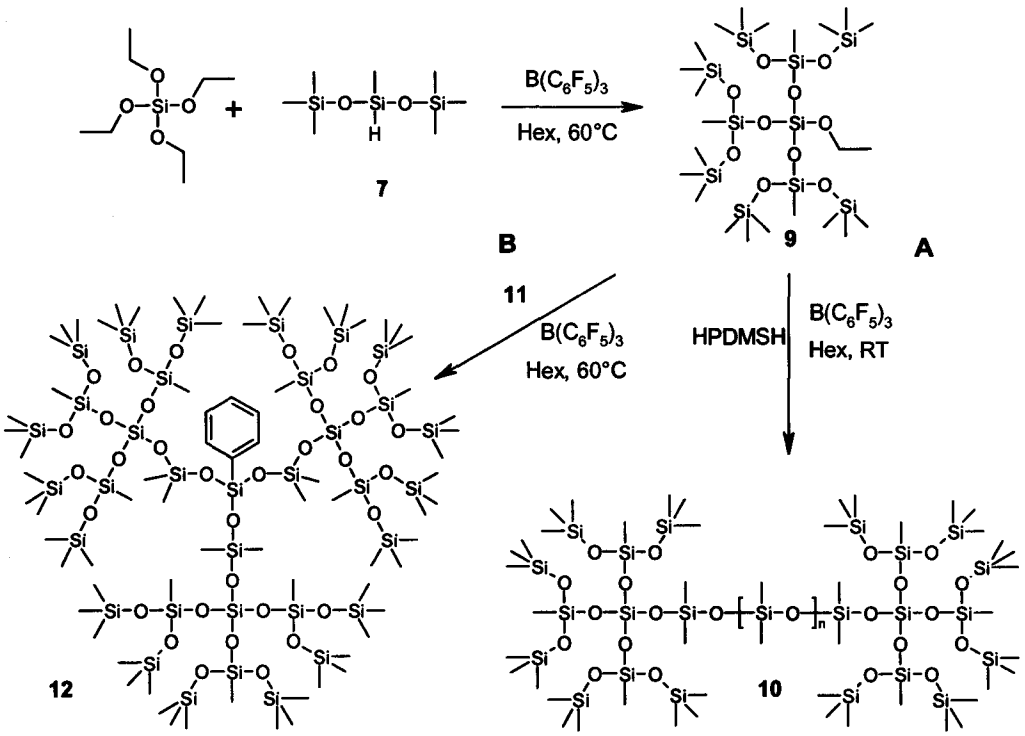


Figure 5.1: Stacked ^{29}Si plot showing purity and diagnostic peak distribution for compounds **6**, **8**, and **9**.

These condensation reactions typically have an induction time, during which, according to Chojnowski,[16] activation of the hydrosilane occurs. However, once reaction is initiated, there is generally an exotherm of sufficient severity that low molecular weight reagents are readily volatilized. This is believed to be the source of the lower yield, for example, of **6** from **3**. While it is possible to mitigate

this effect by efficient cooling, it is more practical to design reagents of appropriate steric bulk such that efficient, yet selective, reaction can occur. As an example, the formation of **9** (Scheme 5.3) occurs cleanly under the conditions described. However, it was not possible to stop the reaction at either intermediate stage ($(R_2R'SiO)_nSi(OR'')_{4-n}$, n = 1,2). Nor could the methoxy analogue of **9** be prepared cleanly from TMOS – that reaction instead produces **8**. The effect of hydrosilane sterics is more pronounced. The reactivity of R_3SiOMe_2SiH is significantly higher than $(R_3SiO)_2MeSiH$, permitting the selective formation of **9**, but also its facile reaction to give **12**.



Scheme 5.3: Synthesis of mono-ethoxy branched siloxane **9** and branched terminal poly(dimethyl)siloxane **10**

5.4 Conclusion

The exquisite control exhibited by these systems relies on careful choice of thermal reaction conditions and appropriate steric bulk on both alkoxysilane and hydrosilane reagents. The reactions with more reactive groups can be rather energetic (*note: methane or other alkanes are released, which could constitute a fire/explosion hazard*) and, if not properly controlled, lead to reduced yield as a consequence of volatilized starting materials. However, these reactions indicate that by appropriately balancing reagents and reaction conditions direct condensation can be favored over metathesis reactions leading to complex 3D branched silicones selectively and in high yield. This process also opens new routes to controlled silicon based materials, including MQ and polyhedral oligomeric silisesquioxane resins (T_n, POSS). In addition to synthesizing these non-functional materials, and developing empirical rules for synthetic control, we will exploit the functional group tolerance of $B(C_6F_5)_3$[13] to prepare functional silicon-based structures with the same high degree of specificity.

5.5 Acknowledgements

We thank the Natural Sciences and Engineering Research Council of Canada for funding this project

5.6 Experimental Details

Materials and methods

Tetramethoxysilane, tetraethoxysilane, tetrapropoxysilane, 1,1,1,3,5,5,5-heptamethyltrisiloxane and tris(pentafluorophenyl)borane were purchased from Aldrich. Pentamethyldisiloxane and phenyl(tris(hydridodimethylsilyloxy))silane were purchased from Gelest. Deuterated chloroform was purchased from Cambridge Isotopes. All of the preceding chemicals were reagent grade and used without further purification. Solvents were purchased from Caledon and purified using pressurized activated alumina columns.

^{1}H, ^{13}C and ^{19}F NMR were recorded using a Bruker AV200 spectrometer (at 200 MHz for H, 50 MHz for C and 188 MHz for F) and ^{29}Si NMR were recorded using a Bruker DRX500 spectrometer (at 99 MHz). ^{1}H, ^{13}C spectra are referenced to residual solvent protons. ^{19}F and and ^{29}Si spectra are unreferenced; for ^{29}Si NMR samples, $Cr(AcAc)_3$ (~0.1 %)was used as a spin relaxation agent. CI-TOF-MS were collected using a Micromass GCT. MALDI-TOF mass spectra were obtained using a Waters Micromass MALDI Micro MX MADLI-TOF mass spectrometer operated in reflectron mode. Samples were dissolved in THF and dithranol was used a matrix.

Synthesis of tetrakis(pentamethyldisilyloxy)silane 6: Comparison of outcomes from different tetraalkoxysilanes

Three reactions were performed in order to determine the effect of steric environment on yield of **6**. Approximately equimolar amounts of tetramethoxysilane **3** (0.2772g, 1.821 mmol), tetraethoxysilane **4** (0.3679g, 1.766

mmol) and tetrapropoxysilane **5** (0.4681g, 1.770 mmol), respectively, were added to 3 separate round bottomed flasks equipped with magnetic stir bars. Pentamethyldisiloxane (3.00 mL, 26.6 mmol) was added to each flask, and the resulting mixture dissolved in hexanes (4 mL) with stirring. Tris(pentafluorophenyl)-borane (0.40mg, 0.00078 mmol in 10 μL toluene solution) was added, and the reactions were allowed to stir at room temperature for 30 min. Excess solvent and starting material were removed *in vacuo*, providing pure **6** by ^{29}Si NMR.

From 3 – 0.9646g, 1.415 mmol; 77% yield.

From 4 – 1.1592g, 1.701 mmol; 96% yield

From 5 – 1.1735g, 1.722 mmol; 97% yield

For characterization, see below.

Synthesis of tetrakis(pentamethyldisilyloxy)silane 6 (with catalyst removal)

Tetrapropoxysilane (0.5832 g, 2.205 mmol) was added to a round bottomed flask equipped with a magnetic stir-bar. Pentamethyldisiloxane (4.00 mL; 35.5 mmol) was added, and the resulting mixture was diluted in hexanes (5 mL). Tris(pentafluorophenyl)borane solution (0.28 mg; 0.00055 mmol in 7 μL toluene) was added with stirring. After an induction period of approximately five minutes, heat was produced, and gas vigorously evolved from solution. The

mixture was stirred at room temperature for 20 minutes prior to the addition of neutral alumina (approx 1g). The resulting slurry was stirred for a further 20 minutes, after which the alumina was removed via filtration. Excess solvent and starting material were removed *in vacuo*, affording pure tetrakis(pentamethyldisilyloxy)silane (1.4561 g, 2.137 mmol, 97% yield).

^{1}H NMR ($CDCl_3$) δ = 0.106 (s, 36H), 0.088 (s, 24H). ^{13}C NMR ($CDCl_3$) δ = 2.0, 1.2. ^{19}F NMR ($CDCl_3$) – no signals visible (32 scans). ^{29}Si NMR ($CDCl_3$ w $Cr(AcAc)_3$) δ = 7.35, -21.22, -109.68. HRMS (CI) calculated for $C_{20}H_{61}O_8Si_9^+$ $[M+H^+]$ = 681.2290, found 681.2286

A sample of **6** (1.0010 g) was chromatographed on silica (50 g; hexanes eluent). The eluent was concentrated on a rotary evaporator and residual solvent was removed *in vacuo*. The resulting compound was spectroscopically identical to **6** and was recovered in high yield (0.9635 g; 96% recovery).

Synthesis of tetrakis(1,1,1,3,5,5,5-heptamethyltrisilyloxy)silane 8

Tetramethoxysilane (1.0071g; 6.616 mmol) was added to a round bottomed flask equipped with a magnetic stir bar and a water jacket condenser. 1,1,1,3,5,5,5-Heptamethyltrisiloxane (10.5 mL; 57 mmol) was added, and the resulting mixture was diluted with hexanes (15 mL).

Tris(pentafluorophenyl)borane (12 mg; 0.023 mmol in 100 µL toluene solution) was added with stirring. After a short induction period (approximately 5 minutes), heat was produced and gas was vigorously evolved from solution. The reaction mixture was stirred at room temperature for 30 minutes, followed by the addition of neutral alumina (~1 g). The resulting slurry was stirred for a further 20 minutes, after which alumina was removed via vacuum filtration over a fritted glass disk. Residual solvent and starting materials were removed *in vacuo*, affording pure (1,1,1,3,5,5,5-heptamethyltrisilyloxy)silane (6.1699 g; 6.308 mmol; 95% yield).

^{1}H NMR ($CDCl_3$) δ = 0.108 (s, 72H), 0.077 (s, 12H). ^{13}C NMR ($CDCl_3$) δ = 1.9, -1.9. ^{19}F NMR ($CDCl_3$) – no signals visible (32 scans). ^{29}Si NMR ($CDCl_3$ w $Cr(AcAc)_3$) δ = 7.43, -66.24, -112.59. HRMS (CI) calculated for $C_{28}H_{85}O_{12}Si_{13}^{+}$ $[M+H^{+}]$ = 977.3042, found 977.3007

Synthesis of ethoxytris(1,1,1,3,5,5,5-heptamethyltrisilyloxy)silane 9

Tetraethoxysilane (2.1800 g; 10.46 mmol) was added to a round bottomed flask equipped with magnetic stir bar and a water jacket condenser. 1,1,1,3,5,5,5-Heptamethyltrisiloxane (12.00 mL; 65.85 mmol) was added, and the resulting mixture was diluted with hexanes (20 mL). The reaction mixture was pre-heated in an oil bath at 60 °C for 15 minutes, at which point tris(pentafluorophenyl)borane (20 mg; 0.039 mmol, in 500 µL toluene solution) was added: gas immediately evolved. The reaction mixture was stirred at 60 °C

for 30 minutes, at which point it was removed from heat and neutral alumina (~2g) was added. The resulting slurry was stirred for a further 30 minutes while cooling to room temperature, before alumina was removed via vacuum filtration over a fritted glass disk. Residual solvent and starting materials were removed *in vacuo*, affording pure ethoxy(1,1,1,3,5,5,5-heptamethyltrisilyloxy)silane (8.0460 g; 10.24 mmol; 98% yield).

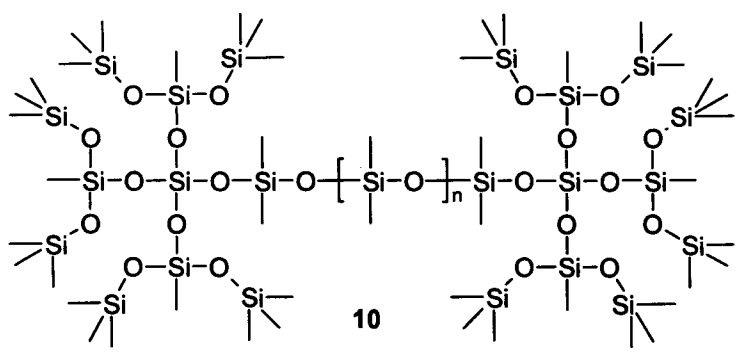
^{1}H NMR ($CDCl_3$) δ = 3.789 (q, 2H, ^{3}J = 7Hz), 1.198 (t, 3H, ^{3}J = 7Hz), 0.107 (s, 54H), 0.066 (s, 9H). ^{13}C NMR ($CDCl_3$) δ = 58.6, 18.2, 1.9, -2.1. ^{19}F NMR ($CDCl_3$) – no signals visible (32 scans). ^{29}Si NMR ($CDCl_3$ w $Cr(AcAc)_3$) δ = 7.68, -65.80, -104.20. HRMS (CI) calculated for $C_{23}H_{69}O_{10}Si_{10}^{+}$ [M+H^{+}] = 785.2584, found 785.2592

Synthesis of branch terminal poly(dimethyl)siloxane 10

Ethoxytris(1,1,1,3,5,5,5-heptamethyltrisilyloxy)silane **9** (0.5001 g; 0.6364 mmol) was added to a round bottomed flask equipped with a magnetic stir bar.. Hydride terminated poly(dimethyl)siloxanes (2-3 cSt; ~653 MW (determined by end group analysis using proton NMR integration), 0.2034 g; 0.3115 mmol) was added to the flask with stirring, and the resulting solution was diluted with dry hexanes (5 mL). Tris(pentafluorophenyl)borane (2.1 mg; 0.0041 mmol in 50 μL toluene solution) was added with stirring. Heat and gas immediately evolved from

solution. The resulting mixture was stirred at room temperature for 20 minutes before addition of neutral alumina (~0.5 g) and stirring for a further 15 minutes. The mixture was filtered and concentrated on a rotary evaporator. Residual solvent was removed *in vacuo*, affording branched terminal-PDMS (0.6718 g; 0.3104 mmol; 97% yield).

^{1}H NMR ($CDCl_3$) δ = 0.134 (s), 0.112 (s), 0.082 (s). ^{13}C NMR ($CDCl_3$) δ = 1.9, 1.2, -1.9. ^{19}F NMR ($CDCl_3$) – no signals visible (32 scans). ^{29}Si NMR ($CDCl_3$ w $Cr(AcAc)_3$) δ = 7.53, -21.32, -21.83, -21.98 ,-22.18, -66.17, -111.87 (a trace of **9** – not separable by chromatography – remained visible in silicon NMR, but was not observed (OEt groups) in the ^{1}H NMR). MALDI-TOF MS: Range of siloxane products found from n = 2 to n = 15. For most abundant component (n=4); calculated $C_{54}H_{162}O_{25}Si_{26}Na^{+}$ [M+Na^{+}] = 1964.53, found 1964.46; calculated $C_{54}H_{162}O_{25}Si_{26}K^{+}$ [M+Na^{+}] calculated 1980.50, found 1980.40.



10

Synthesis of branched siloxane 12

Phenyl(tris(hydridodimethylsilyloxy))silane (0.2504 g; 0.7572 mmol) was added to a round bottomed flask equipped with a magnetic stir bar. Ethoxytris(1,1,1,3,5,5,5-heptamethyltrisiloxy)silane **9** (1.7793 g; 2.2649 mmol) was added, and the resulting solution diluted in hexanes (5 mL). The reaction mixture was pre-heated for 25 minutes in an oil bath at 60 °C, at which point tris(pentafluorophenyl)borane (20 mg; 0.039 mmol in 50 μL toluene solution) was added. After a short induction period, gas evolved from the solution. The reaction mixture was stirred at elevated temperature for 45 minutes. Residual solvent was removed *in vacuo*, affording pure **12** (1.8518g; 0.7129 mmol; 94% yield).
^{1}H NMR ($CDCl_3$) δ = 7.620 (m, 2H), 7.284 (m, 3H), 0.095 (m, 207H). ^{13}C NMR ($CDCl_3$) δ = 134.5 (broad), 129.5, 127.6, 1.9, 1.6, -1.9. ^{19}F NMR ($CDCl_3$) δ = -134.71, -156.16, -163.05. ^{29}Si NMR ($CDCl_3$ w $Cr(AcAc)_3$) δ = 7.49, -19.11, -66.13, -79.57, -111.62. MALDI-TOF MS: calculated 2619.70, found 2619.69.

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Chapter 6: Synthesis of Functional Silicone Architectures via Tris(pentafluorophenyl)borane-Catalyzed Dehydrocarbonative Coupling

David B. Thompson and Michael A. Brook

6.1 Abstract

Functional silicone materials are utilized in a number of reactions, particularly for the purpose of interfacial control. Unfortunately difficulty in synthesizing explicit siloxane structures results in suboptimal properties that are the average result of polydisperse starting materials. The functional group tolerance of tris(pentafluorophenyl)borane catalyzed dehydrocarbonative coupling of silicones is described. Despite previously reported functional group tolerance in related reactions, starting materials bearing Lewis base groups such as epoxides, amines, sulfides and carbonyl groups were found either to inhibit the assembly process (amines), or to lead to very complex reaction mixtures. By contrast, precise siloxane structures featuring alkene and halocarbon functionalities can be quickly synthesized in very high isolated yields with minimal purification. Survey reactions evaluated the availability of the functional siloxanes

for reactions such as platinum catalyzed hydrosilylation and nucleophilic substitutions with chloromethyl silicones. Although nucleophilic substitution with a primary amine results in degradation of the silicone, the reactions of alkenes show promise for further modification.

6.2 Introduction

Siloxane materials are prized in a number of applications due to properties such as high thermal stability and interesting interfacial behaviour.[1, 2] Silicone polymers frequently feature functional groups in order to allow for further modification, for example, the incorporation of hydrophilic entities such as poly(ethylene glycol), as in the synthesis of foam stabilizers, surfactants and super-wetters.[1, 3, 4] Due to the reactive nature of siloxane polymers, the functional groups selected for these transformations must be able to react under mild, pH neutral conditions to avoid equilibration of siloxane backbone. Perhaps the most frequently employed reaction for these purposes is the platinum-catalyzed hydrosilylation of alkenes.[5, 6] This reaction is well understood, and proceeds quickly and cleanly in the absence of functional groups that compete for the SiH group (hydroxyl, amine, carbonyl) or platinum catalyst (thiol or phosphine poisons).[7, 8]

Functional siloxanes are generally synthesized using the same methodology employed for non-functional polymers: ring opening polymerization of cyclic siloxane oligomers. Through the inclusion of functional end groups (e.g.,

1,3-divinyl-11,3,3-tetramethyldisiloxane) or functional cyclics (e.g., 1,3,5,7-tetramethyl-1,3,5,7-tetravinylcyclotetrasiloxane) functionality can be included at the termini, along the polymer backbone, or both (Figure 6.1). Most frequently, this process involves protic-acid catalysis under equilibration conditions, a strategy with poor control that results in inexplicit polymers.[2, 9] As a consequence, siloxane materials synthesized from these processes have properties that are the average result of a broad distribution of products. By gaining greater control over the architectures of the silicones utilized for these applications, it should be possible to obtain polymers with a much a narrower range of properties. Novel assembly processes would also potentially allow for the construction of heretofore unavailable silicone structures, such as those controlled branching. The effects of such structures upon the interfacial properties of siloxane materials are unknown, as no synthetic method to produce functional silicones of this type are currently available.

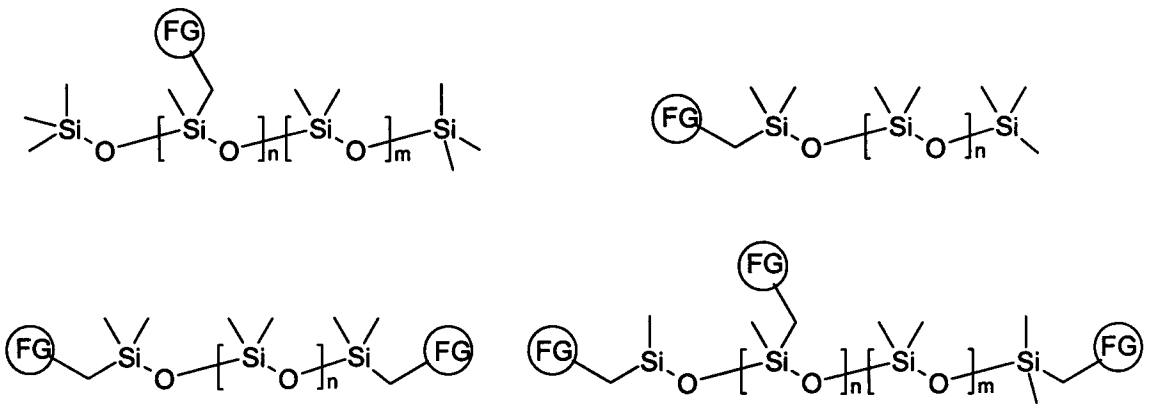


Figure 6.1: Common structural motifs for functional silicones

Tris(pentafluorophenyl)borane (TPFPB **1**) is a Lewis acid catalyst, comparable in strength to boron trifluoride, which finds widespread use as a catalyst and co-catalyst in organic and polymer chemistry.[10] In the last decade, this catalyst has found extensive use in silicon chemistry, primarily in the activation of silyl hydrides for organic transformations. These include silylation of alcohols,[11] and hydrosilylation of carbonyls,[12, 13] thiocarbonyls,[14] imines[15] and olefins[16] (Figure 6.2). Despite its broad reactivity, TPFPB demonstrates good functional group tolerance in organic synthesis and does not require rigorous exclusion of moisture.

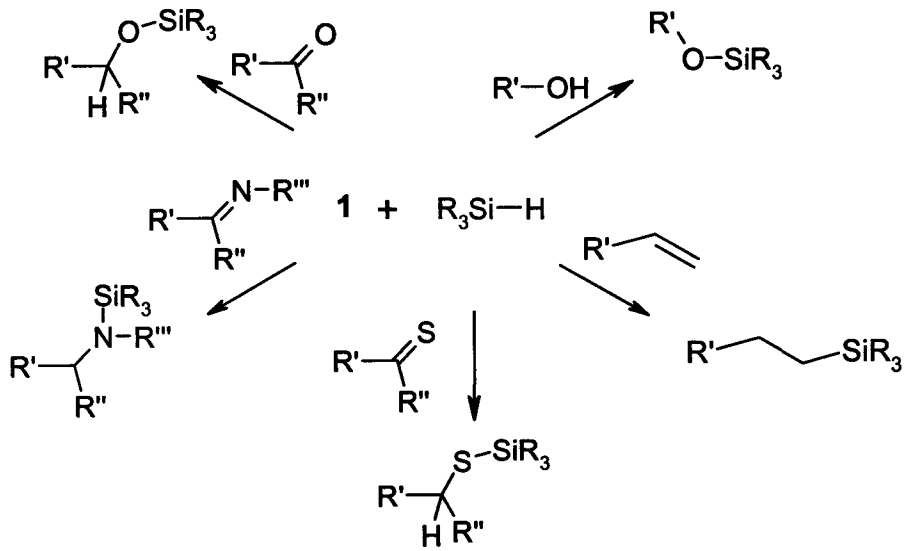


Figure 6.2: Reactions of TPFPB activated hydrosilanes

We have recently reported a method that permits the rapid synthesis of controlled siloxane architectures.[17] Tris(pentafluorophenyl)borane, a strong Lewis acid catalyst, was shown to facilitate the controlled dehydrocarbonative coupling of hydrosilanes with tetraalkoxysilanes. With careful selection of starting

materials and conditions, this process produces only gaseous alkanes as a by-product, and volatile starting materials can be readily removed *in vacuo*. The catalyst could be removed by simply adsorbing the borane to neutral alumina, followed by filtration. While previous investigations into the same coupling reaction with monoalkoxysilanes reported a competing metathetic process,[18] this was not observed in our system. The reaction is particularly attractive due to its non-sensitive nature: reactions can be performed at very high yields (>95%) without rigorous exclusion of water, unlike previously reported chlorosilane condensation reactions.[19]

Given the utility of functional silicone materials, it was of interest to examine the functional group tolerance for tris(pentafluorophenyl)borane-mediated dehydrocarbonative coupling. We report below our examination of dehydrocarbonative coupling reactions with functional silanes containing amines, thiols, epoxides, esters, alkene and organohalide groups. For some of the products, further manipulation of the functional group is reported.

6.3 Results and Discussion

The basic reaction to be exploited in the rapid assembly of functional silicones is the tris(pentafluorophenyl)borane-catalyzed reaction between hydrosilanes and alkoxysilanes, which yields disiloxanes (e.g., Scheme 6.1). As in our previous investigation, sterics were shown to have a considerable effect on the reaction rate, and balancing sterics was found to be essential for optimal

reaction rates.[17] Reacting less hindered SiH compounds with less hindered alkoxysilanes leads to an uncontrolled exotherm, volatilizing starting materials and providing decreased yields. At the other extreme, increasing steric hindrance at both reacting centers decreases reactivity such that the reactions will not proceed at room temperature.

The ability to introduce functional groups to silicones using boron catalyzed dehydrocarbonation was examined on a variety of functional groups, including amines, thiols, epoxides, alkenes and haloalkyl groups, as these groups are widely used in silicone polymers. The analysis of non-specific reactions is first reported, followed by the selective processes observed with alkenes and chloroalkyl-substituted compounds.

6.3.1 Incompatible Functionality

The reactions of silanes possessing Lewis basic functional groups did not display the same high yield of pure product previously observed with this reaction. In the presence of amines, reaction was completely suppressed – only starting materials were recovered. It seems likely that the equilibrium involving complexation of the Lewis basic amine with Lewis acidic boron leaves little free catalyst. This outcome was not anticipated, as boron-catalyzed hydrosilylation of imines occurs efficiently, albeit at much higher catalyst concentrations.[15] The high yields reported by Piers for TPFPB activated SiH silylation of alcohols

suggests that dehydrocarbonative coupling (a potential side reaction) does not proceed in the presence of free alcohol. [11] It is possible that a similar effect results in the presence of free amine.

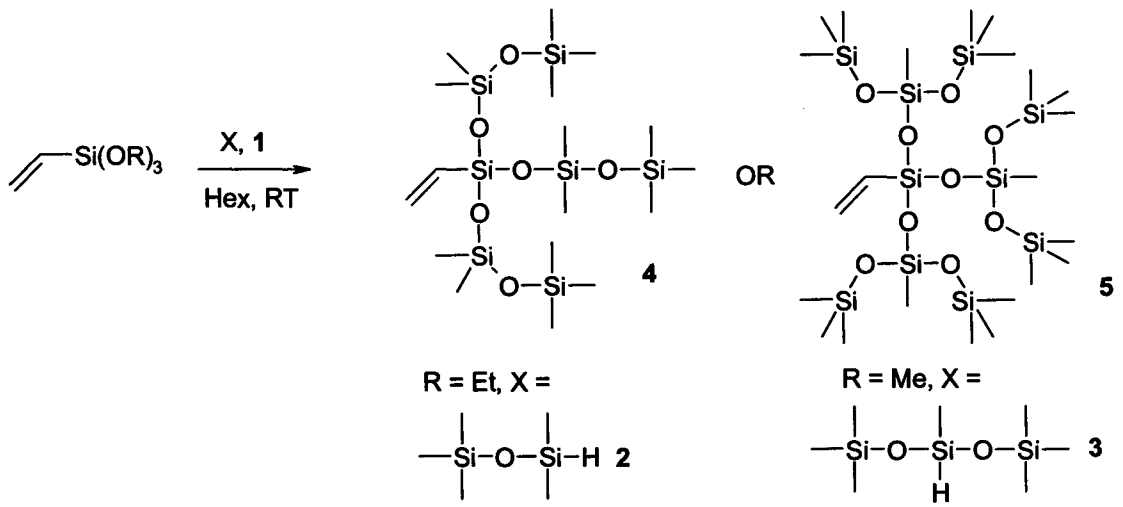
The remaining reactions with compounds bearing a variety of functional groups including acrylates, thiols, esters, and epoxides, occurred, but led to complicated product mixtures. The reaction of 3-mercaptopropyltriethoxysilane with **3** showed near complete removal of the methoxysilyl groups. However, this reaction also produced a number of unexplained new methylsilyl peaks in the proton, carbon and silicon NMR. These cannot be explained by thio-silylation alone, and may be the result of as yet unknown side reactions.

In the reactions of pentamethyldisiloxane **2** or 1,1,1,3,5,5,5-heptamethyltrisiloxane **3** with (3-glycidyloxypropyl)trimethoxysilane, 3-(trimethoxysilyl)propyl methacrylate and 3-(triethoxylsilyl)propoxytribenzylcitrate, respectively, complex mixtures of products were observed. It has not yet been possible to establish if these are the result of catalyst deactivation, competing alkene hydrosilylation (acrylate), reductive debenzylation (citrate), epoxide opening (3-glycidyloxypropyl)trimethoxysilane), metathetic processes or combinations of these. Irrespective, the processes are grossly inferior in selectivity when compared to the formation of simple silicones and are currently of no practical significance.

6.3.2 Alkene Functional Siloxanes

Unlike the heteroatom-modified alkoxysilanes, alkene functional alkoxysilane starting materials showed great tolerance to the dehydrocarbonative coupling. For example, vinyltriethoxysilane reacted with **2** to form vinyl functional siloxane **4** in 94% isolated yield (Scheme 6.1). Despite the reported ability of tris(pentafluorophenyl)borane to catalyze hydrosilylation of alkenes,[16] ^{13}C NMR revealed preservation of the vinyl sp^2 carbons. The absence of observed hydrosilylation may be a consequence of two factors: catalyst concentration and the related relative reaction rates. The established protocol for hydrosilylation calls for 5 – 10 mol % of **1**, and the reaction generally takes 10 – 12 hours to reach completion.[16] By contrast, the synthesis of **4** required only 0.06 mol % catalyst,‡‡ and the reaction was complete in under 30 minutes, conditions under which hydrosilylation is not a competitive process. The corresponding branched vinyl-siloxane **5** was synthesized in >99% yield by reaction of **3** with vinyltrimethoxysilane (Scheme 6.1).

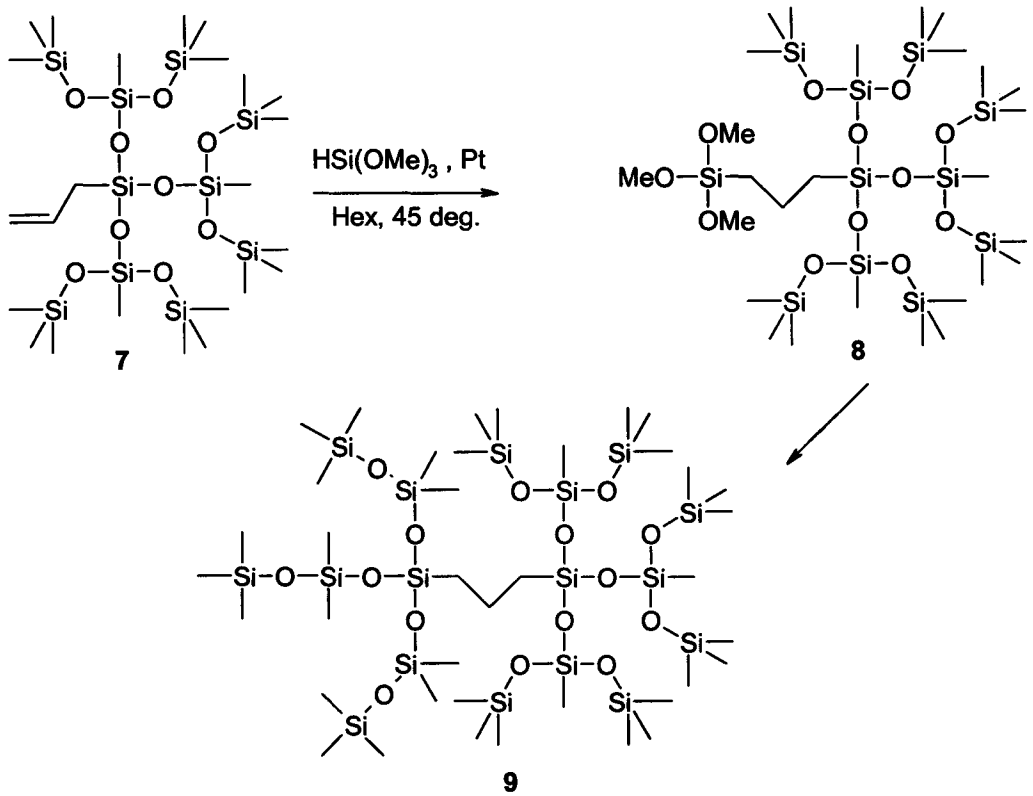
‡‡ Based on molar ratio of TPFPB to ethoxysilyl groups



Scheme 6.1: Synthesis of vinyl-functional siloxane architectures 4 and 5

Allyl groups, another functional group broadly exploited in silicone chemistry, also participated efficiently in the condensation process: reactions of **2** and **3** with the sterically appropriate allyltrialkoxysilane gave allyltris(pentamethyldisilyloxy)-silane **6** (95% yield) and allyltris(1,1,1,3,5,5,5-heptamethyltrisilyloxy)silane **7** (> 99% yield), respectively. It was necessary to establish that these allyl groups were still available for common organosilicon transformations. To that effect, trimethoxysilane was grafted to **7** using hydrosilylation catalyzed by Karstedt's platinum solution.[7] The reaction took place over 48 hours at 45 °C, leading to trimethoxy functional branched siloxane **8**, although with some contamination from hexamethoxydisiloxane. This compound was further reacted with **2** in the presence of **1** to form asymmetrical siloxane structure **9**. It was not possible to isolate this structure, as the contaminant co-eluted; however, ^{29}Si NMR data

(after subtracting peaks associated with contaminants) showed this as the alternative product.



Scheme 6.2: Synthesis of asymmetrical siloxane architecture

6.3.3 Halocarbon Functional Siloxanes

Piers has reported that silylation of alcohols utilizing TPFPB activated Si-H compounds proceeds cleanly in the presence of carbon bromine bonds.[11] A corresponding tolerance to alkyl halides in the dehydrocarbonative coupling reaction could allow for the introduction to silicones of groups of interest (e.g.

hydrophilic moieties) through nucleophilic substitution. With that in mind, 3-chloropropyltrimethoxysilane was reacted with **3** in the presence of 0.05% TPFPB to form branched chloropropylsiloxane **10** in 99% isolated yield. The reactivity of chloropropylsilanes towards nucleophilic substitution at carbon is comparable to that of conventional alkyl chlorides;[20] the carbon spacer mitigates any effect of silicon. Chloromethyl groups are known to possess increased reactivity compared to chloropropyl groups, likely due to electronic effects of silicon. The presence of more reactive electrophiles on silicone precursors should be advantageous as they may allow for the use of milder nucleophiles less likely to degrade the silicone in subsequent functionalization steps.

TPFPB catalysis of **2** or **3** with chloromethyltriethoxysilane or chloromethyl-trimethoxysilane, respectively, gave chloromethyltris(pentamethyldisilyloxy)silane **11** (96%) and chloromethyl-tris(1,1,1,3,5,5,5-heptamethyltrisilyloxy)silane **12** (>99%) in very high yield. In order to probe the reactivity of the chloromethyl group in the products, substitution of **12** was attempted with diethylenetriamine. After 2 hours at 100 °C, very small amounts (~5%) of substituted product were visible in the ^{1}H NMR. After 24 hours, the chloromethyl peak had been completely removed, however multiple methylsilyl peaks indicated that degradation of the siloxane architecture also occurred, as is expected in the presence of bases. Further work will be necessary to optimize substitution reactions of these functional siloxanes without damaging the previously assembled siloxane.

Silicones are noted for their interfacial characteristics, especially in co-polymer systems. This can be seen in the case of fluorosilicones: the properties obtained with the combination of hydrophobic and lyophobic moieties are valued in a number of applications.[21] The ability of TPFPB catalyzed dehydrocarbonative coupling to proceed in the presence of organohalides suggests that this strategy could be effective for the assembly of controlled silicone-fluorocarbon copolymers. In order to establish this, commercially available tridecafluorooctyltriethoxysilane was reacted with **2** to create silicone-fluorocarbon **13** in 91% isolated yield. The properties of conventional fluorosilicone fluids and materials are the result of the average properties of their siloxane component, usually an equilibrated, polydisperse mixture. Compounds such as **13**, synthetically unavailable through conventional methods, should have a much narrower range of properties; this hypothesis is currently under investigation.

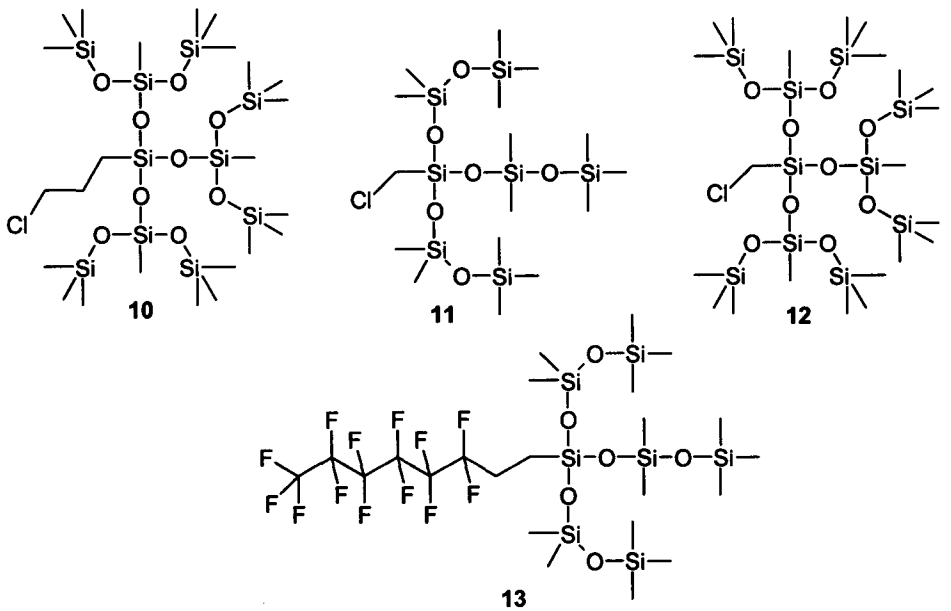
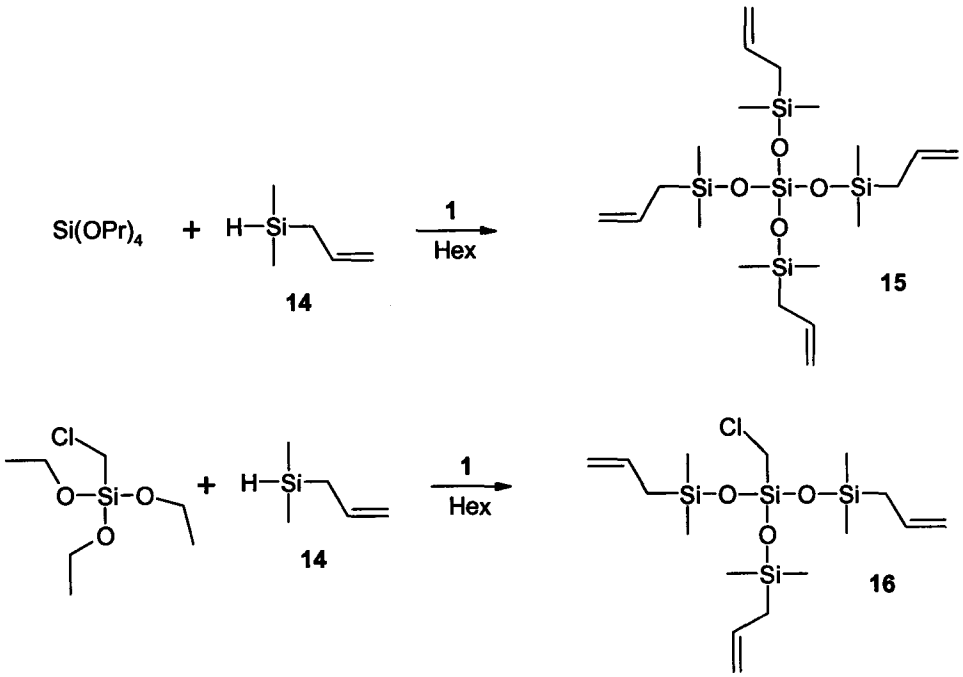


Figure 6.3: Halocarbon functional siloxane architectures

6.3.4 Multi-Functional Siloxanes

The successful reaction of hydrosiloxanes with organochloro and allyl functional alkoxysilanes made the investigation of allyl-functional hydrosilanes attractive. The reaction of allyldimethylsilane **14** with tetrapropoxysilane gives tetrakis(allyldimethylsilyloxy)silane **15** with relatively small amounts (25 – 30%) of propoxytris(allyldimethylsilyloxy)silane persisting as a contaminant. This tri-reacted product was not separable through column chromatography. It is possible that this is due to the high volatility of **14** leading to its removal through evaporation under the highly exothermic reaction conditions. A similar result was observed for the corresponding reaction of chloromethyltriethoxysilane with **14** to form chloromethyltris(allyldimethylsilyloxy)silane **16**. The desired product is the

primary component of the crude reaction mixture, with residual ethoxysilane indicating the presence of small amounts of di-reacted product (~20%). These syntheses require optimization, but multifunctional compounds of this type are attractive precursors for new, well defined siloxane materials (**Scheme 6.3**).



Scheme 6.3: Synthesis of multifunctional siloxanes **15** and **16**

The high yields available for explicit siloxane structures featuring organohalide and alkene functionality demonstrates the relatively broad generality of tris(pentafluorophenyl)borane catalyzed dehydrocarbonative coupling of hydrosilanes and alkoxysilanes. Future research will be directed towards the synthesis of larger explicit, functional siloxanes as well as subsequent modification with hydrophilic or superhydrophobic moieties. Additionally, further functional group transformations (epoxidation, substitution

etc.) of the alkene and chloroalkyl will be explored in order to obtain functionality which was found to be incompatible with the TPFPB assembly process.

6.4 Conclusion

It has been demonstrated that tris(pentafluorophenyl)borane catalyzed dehydrocarbonative coupling of hydrosilanes and alkoxysilanes represents a feasible route to precisely controlled branched siloxane architectures. This process allowed for the rapid synthesis of alkene and halocarbon functional siloxane architectures in near quantitative yields. More electron rich functional groups interfered with the reaction, leading to a mix of unknown products. The demonstrated reactivity of allyl and chloromethyl functional siloxane architectures suggests that they can serve as starting materials for the synthesis of more complex siloxane architectures and silicone-based copolymers.

6.5 Experimental Section

Materials and methods

Chloropropyltrimethoxysilane, mercaptopropyltrimethoxysilane and tris(pentafluorophenyl)borane were purchased from Aldrich. All other silicon-containing reagents were purchased from Gelest. Deuterated chloroform was purchased from Cambridge Isotopes. These chemicals were reagent grade and used without further purification. Solvents were purchased from Caledon and dried and purified using pressurized activated alumina columns.

^{1}H, ^{13}C and ^{19}F NMR were recorded using a Bruker AV200 spectrometer (at 200 MHz for ^{1}H, 50 MHz for ^{13}C and 188 MHz for ^{19}F); ^{29}Si NMR were recorded using a Bruker DRX500 spectrometer (at 99 MHz). ^{1}H, ^{13}C spectra are referenced to residual solvent protons. ^{19}F and ^{29}Si spectra are unreferenced; for ^{29}Si NMR samples, $Cr(AcAc)_3$ (~0.1 %) was used as a spin relaxation agent. CI-TOF-MS were collected using a Micromass GCT.

Synthesis of Vinyltris(pentamethyldisilyloxy)silane 4

Vinyltriethoxysilane (2.0939g, 11.002 mmol) and pentamethyldisiloxane (10.00 mL, 7.6 g, 54 mmol) were combined in a round bottomed flask equipped with a magnetic stir bar. The reaction mixture was diluted in hexanes (5.00 mL) followed by the addition of tris (pentafluorophenyl)borane (0.0010 g; 0.00195 mmol in 25 µL toluene solution). Within 5 min, gas and heat evolved from solution. The reaction was stirred at RT for 30 minutes before the addition of neutral alumina (~1g), and the resulting slurry stirred for a further 30 min. Alumina was removed by filtration over a fritted glass disk. Residual solvent and starting materials were removed *in vacuo*, affording pure vinylltris(pentamethyldisilyloxy)silane (5.6219 g, 10.31 mmol, 94% yield).

^{1}H NMR: δ = 5.92 (m, 3H), 0.11 (s, 45H)

^{13}C NMR: δ = 134.2, 133.6, 2.0, 1.3

^{19}F NMR: No signals visible after 32 scans

^{29}Si NMR: δ = 7.37, -21.23, -81.80

HRMS (TOF MS ES+) calculated for $C_{17}H_{52}NO_6Si_7^+$ [M+NH_4^+] = 562.2100, found 562.2153

Synthesis of Vinyltris(1,1,1,3,5,5,5-heptamethyltrisilyloxy)silane 5

Vinyltrimethoxysilane (1.1339 g, 7.649 mmol) and 1,1,1,3,5,5,5-heptamethyltrisiloxane (10.0 mL, 8.19 g, 36.81 mmol) were combined in a round bottomed flask equipped with a magnetic stir bar. The reaction mixture was diluted in hexanes (5.00 mL) followed by the addition of tris(pentafluorophenyl)borane (0.0010 g; 0.00195 mmol in 25 µL toluene solution). After stirring at room temperature for 10 min without reaction, additional catalyst was added (0.0010 g; 0.00195 mmol in 25 µL toluene solution; 0.0020g, 0.0039 mmol total), at which point gas and heat immediately began to evolve from solution. The reaction was stirred at RT for 30 min before the addition of neutral alumina (~1g), and the resulting slurry stirred for a further 30 min. Alumina was removed by filtration over a fritted glass disk. Residual solvent and starting materials were removed *in vacuo*, affording pure vinyltris(1,1,1,3,5,5,5-heptamethyltrisilyloxy)silane (5.8608 g, 7.63 mmol, 100 % yield)

^{1}H NMR: δ = 5.94 (s, broad, 3H), 0.11 (s, 54H), 0.04 (s, 9H)

^{13}C NMR: δ = 134.2, 133.2, 1.9, -1.7

^{19}F NMR: No signals visible after 32 scans

^{29}Si NMR: δ = 7.56, -66.00, -83.54

HRMS (TOF MS ES+) calculated for $C_{23}H_{70}NO_9Si_{10}^+$ [M+NH_4^+] = 784.2743, found 784.2771

Synthesis of allyltris(pentamethyldisilyloxy)silane 6

Allyltriethoxysilane (3.0291g, 14.8238 mmol) and pentamethyldisiloxane (11.46 mL, 8.7 g, 58.64 mmol) were combined in a round bottomed flask equipped with a magnetic stir bar. The reaction mixture was diluted in hexanes (8.00 mL) followed by the addition of tris(pentafluorophenyl)borane (0.0020 g; 0.0039 mmol in 50 µL toluene solution). Gas and heat immediately evolved from solution. The reaction was stirred at RT for 35 min before the addition of neutral alumina (~1g), and the resulting slurry stirred for a further 40 min. Alumina was removed by filtration over a fritted glass disk. Residual solvent and starting materials were removed *in vacuo*, affording pure allyltris(pentamethyldisilyloxy)silane (7.8739 g, 14.081 mmol, 95% yield).

^{1}H NMR: δ = 5.78 (sextet, ^3J = 8 Hz 1H), 4.91, (m, broad, 2H), 1.55 (d, ^3J = 8 Hz 2H), 0.10 (s, 27H), 0.07 (s, 18H)

^{13}C NMR: δ = 134.2, 114.9, 22.2, 1.9, 1.2

^{19}F NMR: No signals visible after 32 scans

^{29}Si NMR: δ = 7.37, -21.75, -73.59

HRMS (TOF MS ES+) calculated for $C_{18}H_{54}NO_6Si_7^+$ [M+NH_4^+] = 576.2336, found 576.2327

Synthesis of Allyltris(1,1,1,3,5,5,5-heptamethyltrisilyloxy)silane 7

Allyltrimethoxysilane (1.9998 g, 12.32 mmol) and 1,1,1,3,5,5,5-heptamethyltrisiloxane (13.40 mL, 11.05 g, 49.70 mmol) were combined in a round bottomed flask equipped with a magnetic stir bar. The reaction mixture was diluted in hexanes (10.00 mL) followed by the addition of tris(pentafluorophenyl)borane (0.0080 g; 0.0156 mmol in 200 µL toluene solution). After a short induction period (<1 min), gas and heat evolved vigorously from solution. The reaction was stirred at RT for 45 min before the addition of neutral alumina (~2g), and the resulting slurry stirred for a further 45 min. Alumina was removed by filtration over a fritted glass disk. Residual solvent and starting materials were removed *in vacuo*, affording pure allyltris(1,1,1,3,5,5,5-heptamethyltrisilyloxy)silane (9.7429 g, 12. mmol, 100 % yield)

^{1}H NMR: δ = 5.82 (sextet, ^{3}J = 8 Hz, 1H), 4.91 (m, 2 H), 1.58 (d, ^{3}J = 8 Hz, 2H), 0.11 (s, 54H), 0.07 (s, 9H)

^{13}C NMR: δ = 133.6, 114.5, 22.1, 1.9, -1.9

^{19}F NMR: No signals visible after 32 scans

^{29}Si NMR: δ = 7.57, -66.15, -74.89

HRMS (TOF MS ES+) calculated for $C_{24}H_{72}NO_9Si_{10}^{+}$ [M+NH_4^+] = 798.2900, found 798.8920

Synthesis of trimethoxy functional branched siloxane 8

Allylsiloxane **7** (0.5002 g, 0.6407 mmol) was dissolved in hexanes (3.00 mL) in a round bottomed flask equipped with stir bar and water jacked condenser with drying tube (Drierite desiccant). Trimethoxysilane (0.0874 g, 0.7152 mmol) was added, followed by Karstedt's platinum complex (15 µL; 2% solution in xylenes), after which the reaction flask was immersed in an oil bath at 45 °C. The reaction was allowed to proceed for 48 h, at which point activated charcoal (~0.25 g) was added, and the resulting mixture stirred for a further 2 h. The crude reaction mixture was filtered over Celite, and residual solvent was removed *in vacuo*, affording crude **8** (0.2471 g). Residual trimethoxysilane and the byproduct hexamethoxydisiloxane were visible in the NMR spectra.

^{1}H NMR: δ = 3.58 (m 12H), 1.55 (m, 2H), 0.65 (m, 4H), 0.09 (s, 54H), -0.20 (s, 9H)

^{13}C NMR: δ = 51.3, 50.5, 50.3, 18.8, 16.7, 13.7, 1.9, -1.9

^{29}Si NMR: δ = 7.56, -42.21, -51.12 ($HSi(OMe)_3$), -66.06, -70.95, -85.815 ($(((MeO)_3Si)_2O$)

Synthesis of asymmetrical branched siloxane 9

A sample of crude product from **8** combined with pentamethyldisiloxane (2.00 mL, 1.20 g, 8.09 mmol) in a round bottomed flask equipped with a magnetic stir bar. Tris(pentafluorophenyl)borane (0.0010 g; 0.00195 mmol in 25 µL toluene solution) was added. Immediately upon addition, gas and heat evolved from solution. The reaction mixture was allowed to stir at RT for 1 h, at which point

residual starting materials were removed *in vacuo*. Contaminant peaks from reaction with hexamethoxydisiloxane were also visible.

^{1}H NMR: δ = 1.47 (m, 2H), 0.62 (m, 4H) 0.10 (m, 117H)

^{13}C NMR: δ = 19.7, 19.5, 16.9, 1.9, 1.7, 1.4, -1.7

^{29}Si NMR: δ = 7.36, 7.27, 7.05, 6.96, -21.36, -21.99, -66.28, -69.12, -70.675

Synthesis of 3-chloropropyltris(1,1,1,3,5,5,5-heptamethyltrisilyloxy)silane 10

3-Chloropropyltrimethoxysilane (1.0705 g, 5.3870 mmol) and 1,1,1,3,5,5,5-heptamethyltrisiloxane (7.370 mL, 6.036 g, 27.13 mmol) were combined in a round bottomed flask equipped with a magnetic stir-bar. The mixture was diluted with hexanes (7 mL) and tris(pentafluorophenyl)borane (0.0021g, 0.0041 mmol, in 50 μL toluene solution) was added. After a short induction period (< 5 min), gas and heat evolved steadily from solution. The reaction mixture was stirred until cool (30 min), followed by the addition of neutral alumina (~ 1 g). The resulting slurry was stirred for a further 30 min, after which alumina was removed by filtration over a fritted glass disk. Residual solvent and starting materials were removed *in vacuo*, affording pure 3-chloropropyltris(1,1,1,3,5,5,5-heptamethyltrisilyloxy)silane (4.3645 g, 5.3344 mmol, 99% yield).

^{1}H NMR: δ = 3.51 (t, 2H, ^{3}J = 6 Hz), 1.91 (m, 2H), 0.67 (m, 2H), 0.12 (s, 54H), 0.069 (s, 9H)

^{13}C NMR: δ = 47.6, 27.0, 12.1, 1.9, -1.9

^{19}F NMR: No signals visible after 64 scans

^{29}Si NMR: δ = 7.72, -66.10, -71.29

HRMS (TOF MS ES+) calculated for $C_{24}H_{73}NO_9Si_{10}Cl^+$ $[M+NH_4^+]$ = 834.2667, found 834.2643

Synthesis of chloromethyltris(pentamethyldisilyloxy)silane 11

Chloromethyltriethoxysilane (1.0436 g, 4.905 mmol) and pentamethyldisiloxane (5.00 mL, 3.8 g, 27 mmol) were combined in a round bottomed flask equipped with a magnetic stir bar. The stirring reaction mixture was diluted in hexanes (5.00 mL) followed by the addition of tris(pentafluorophenyl)borane (0.868 mg, 0.00170 mmol in 20 µL toluene solution). Within 1 min, gas and heat evolved from solution. The reaction was stirred at room temperature for 45 min. Neutral alumina (~1 g) was added, and the resulting slurry was stirred for a further 20 min, after which alumina was removed by filtration over a fritted glass disk. Residual solvent and starting materials were removed *in vacuo*, affording pure chloromethyltris(pentamethyldisilyloxy)silane (2.6786 g, 4.719 mmol, 96% yield).

^{1}H NMR: δ = 2.66 (s, 2H), 0.11 (s, 45H)

^{13}C NMR: δ = 26.6, 1.9, 1.1

^{19}F NMR: No signals visible after 32 scans

^{29}Si NMR: δ = 7.76, -20.425, -80.57

HRMS (TOF MS ES+) calculated for $C_{16}H_{51}NO_6Si_7Cl^+$ $[M+NH_4^+]$ = 584.1790, found 584.1799

Synthesis of chloromethyltris(1,1,1,3,5,5,5-heptamethyltrisilyloxy)silane 12

3-Chloromethyltrimethoxysilane (1.0127 g, 5.9337 mmol) and 1,1,1,3,5,5,5-heptamethyltrisiloxane (6.37 mL, 5.21 g, 23.45 mmol) were combined in a round bottomed flask equipped with a magnetic stir-bar. The mixture was diluted with hexanes (7 mL) and tris(pentafluorophenyl)borane (0.0021g, 0.0041 mmol, in 50 µL toluene solution) was added. After a short induction period (< 1 min) gas and heat evolved vigorously from solution. The reaction mixture was stirred while cooling to room temperature (30 min), followed by the addition of neutral alumina (~ 1 g). The resulting slurry was stirred for a further 20 min, after which alumina was removed by filtration over a fritted glass disk. Residual solvent and starting materials were removed *in vacuo*, affording pure 3-chloromethyltris(1,1,1,3,5,5,5-heptamethyltrisilyloxy)silane (4.7559 g, 6.0195 mmol, 100% yield).

^1H NMR: δ = 2.68 (s, 2H), 0.12 (s, 54H), 0.03 (s, 9H)

^{13}C NMR: δ = 26.4, 1.9, -2.1

^{19}F NMR: No signals visible after 64 scans

^{29}Si NMR: δ = 8.01, -65.76, -82.07

HRMS (TOF MS ES+) calculated for $C_{24}H_{73}NO_9Si_{10}Cl^+$ $[M+NH_4^+]$ = 834.2667, found 834.2643

Synthesis of tridecafluorooctyltris(pentamethyldisilyloxy)silane 13

Tridecafluorooctyltriethoxysilane (0.5174 g, 1.0138 mmol) and pentamethyldisiloxane (2.00 mL, 1.20 g, 8.09 mmol) were combined in a round bottomed flask equipped with a magnetic stir bar. Tris(pentafluorophenyl)borane (0.0004 g, 0.7812 mmol in 10 μL toluene solution) was added. After a short induction period (~4 min), heat and gas evolved from solution. The reaction was stirred at RT for 20 min, at which point neutral alumina (~ 1 g) was added, and the resulting slurry stirred for an additional 20 min. The reaction mixture was diluted in hexanes and filtered over a fritted glass disk to remove alumina, and residual solvent and starting materials were removed *in vacuo*, affording tridecafluorooctyltris(pentamethyldisilyloxy)silane (0.8023 g, 0.9273 mmol, 91% yield).

^{1}H NMR: δ = 2.14 (m, broad, 2H), 0.77 (m, 2H) 0.09 (s, 45H)

^{13}C NMR: δ = 25.6 (t), 4.1, 1.8, 0.8

^{19}F NMR: -80.9, -116.4, -122.0, -123.0, -123.5, -126.3

Synthesis of tetrakis(allyldimethylsilyloxy)silane 15

Tetrapropoxysilane (1.0305 g, 3.8969 mmol) and allyldimethylsilane (2.4008 g, 23.950 mmol) were combined in a round bottomed flask equipped with a magnetic stir bar. The reaction was diluted in hexanes (5.00) mL) and tris(pentafluorophenyl)borane (0.0021g, 0.0041 mmol, in 50 μL toluene solution)

was added. After a short induction period (< 5 min) gas and heat evolved from solution. The reaction was stirred for 20 min, at which point neutral alumina (~ 1 g) was added, and the reaction continued to stir for a further 20 min. The resulting slurry was filtered over a fritted glass disk to remove alumina, and residual solvent and starting materials were removed *in vacuo*, yielding a clear oil as a final product (1.8413 g). NMR spectroscopy revealed this to be tetrakis(allyldimethylsilyloxy)silane, with approximately 25% propoxytris-(allyldimethylsilyloxy)silane as a contaminant.

^{1}H NMR: δ = 5.81 (sextet, 4H, ^{3}J = 8 Hz), 4.89 (m, 8H), 1.60 (d, 8H, ^{3}J = 8 Hz,), 0.12 (s, 24H) with contaminants visible at 3.62 (t, 0.45H, ^{3}J = 7 Hz,), and 0.91 (t, 0.62H, ^{3}J = 7 Hz, Hz)

^{13}C NMR: δ = 134.1, 113.6, 26.0, -0.5 with contaminants visible at 64.7, 25.4, 10.3

Synthesis of chloromethyltris(allyldimethylsilyloxy)silane 16

Chloromethyltriethoxysilane (1.0085 g, 4.7403 mmol) and allyldimethylsilane (1.9890 g, 19.84 mmol) were combined in a round bottomed flask equipped with a magnetic stir bar. The reaction was diluted in hexanes (5.00 mL) and tris(pentafluorophenyl)borane (0.0021g, 0.0041 mmol, in 50 µL toluene solution) was added. After a short induction period (< 5 min), gas and heat evolved from solution. This reaction was stirred for 45 min while cooling to room temperature, at which point neutral alumina (~1 g) was added. The

resulting slurry was stirred for a further 30 min after which alumina was removed via filtration over a fritted glass disk. Residual solvent and starting materials were removed *in vacuo*, yielding a clear oil as a final product (1.8287 g). NMR spectroscopy revealed this to be chloromethyltris(allyldimethylsilyloxy)silane, with approximately 20% chloromethylethoxybis(allyldimethylsilyloxy)silane as a contaminant.

^{1}H NMR: δ = 5.78 (sextet, ^{3}J = 8 Hz, 3H), 4.90 (m, 6H), 2.61 (s, 1H), 1.63 (d, ^{3}J = 8 Hz, 6H), 0.11 (s, 18H) with contaminants visible at 3.82 (q, ^{3}J = 7 Hz,0.48H), 2.67 (s, 0.52H), 1.22 (t, ^{3}J = 7 Hz, 0.8H)

^{13}C NMR: δ = 133.9, 113.8, 25.9, -0.4 with contaminants visible at 58.9, 26.4, 18.3

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Chapter 7: General Conclusions

The valuable properties of silicones are a consequence of their hybrid organic/inorganic structure, the dynamic nature of which sets them apart from their organic relatives. The reactive nature of siloxane materials raises challenges when trying to gain control over polymer architecture through conventional synthetic methods, limiting the availability of well defined silicone systems. However, these same properties also create opportunities for innovation in the synthesis and modification of siloxane architectures. Throughout this document, we have reported our efforts to increase synthetic control in the synthesis and modification of siloxane materials by taking advantage of the properties of silicones and the reactivity of hydrosilanes.

In Chapter 2 methods to manipulate hydrophilic domains in silicones were developed. A novel process to prepare generic SiH rich elastomers is reported, and these were used to graft allyl PEO to the silicones through hydrosilylation. The size and functionality (mono- or di- allyl) of the grafting polymer was found to influence the density and morphology of grated PEO at the elastomer surface, providing a means by which these properties could be controlled. This provides opportunities for future efforts to gain higher degrees of control over the surface properties of PEO functional siloxane elastomers. Additionally, a system was discovered in which the interfacial properties of silicones resulted in structured elastomers: the co-cure of allyl functional PEO with SiH rich silicones leads to

preferential migration of SiH functional groups to the surface, sequestering hydrophilic PEO domains at the interior of the elastomer.

In Chapter 3, we established a viable synthetic methodology for the stratification of siloxane elastomers. Solvents which swell siloxane elastomers, but in which substrates do or don't dissolve, were used to provide or decline a mechanism of transport across the polymer membrane to the interior of a SiH rich elastomer. This allowed independent manipulation of the exterior and interior of a silicone elastomer. This system was used to graft hydrophilic polymers exclusively at the surface of an elastomer while preserving interior functionality. Subsequent reactions in appropriate solvents modified the interior of the elastomer with amines, additional crosslinks, hydrophobic moieties and platinum nanoparticles, demonstrating broad utility. Structured elastomers of this type may have great application in future silicone-based devices.

Chapter 4 reported on the development of hydrodiisopropylsilanes as covalent tethers for the linkage of silicones and carbohydrates. Unlike conventional systems for silicone-carbohydrate copolymers, this strategy uses direct C-O-Si linkages, employing sterically significant alkyl groups at silicon to gain hydrolytic stability. Hindered linkages of this type were found to allow for control over grafting locus at the carbohydrate, both through the use of protecting groups, and, significantly, with unprotected glucose. The practicality of linkages of this type may allow for their use the future synthesis of silicone-biopolymer copolymers.

Chapter 5 explored the tris(pentafluorophenyl)borane-catalyzed dehydrocarbonative coupling of hydrosilanes and alkoxysilanes. This reaction was found to permit rapid assembly of explicit branched siloxane architectures in near quantitative yields. Further, exquisite control over the reactions was possible through manipulation of steric factors at both the hydrosilane and alkoxysilanes. The synthesis of branched ethoxy functional silicones allowed the assembly of larger siloxane structures, both with hydrosilane terminated PDMS and with a trifunctional core to make a dendritic structure.

In Chapter 6, we report on the functional group tolerance of the TPFPB catalyzed dehydrocarbonative coupling reaction. Lewis basic structures were found inhibit the reaction, either through catalyst combination or a variety of competitive reactions. By contrast, organohalides and alkenes did not exhibit any effect on the reaction, allowing synthesis of explicit, functional branched siloxanes. As in previous studies, reactions were found to give near quantitative yields at low catalyst loading with minimal purification. These functional materials will serve as starting materials for future synthesis of larger siloxane architectures and co-polymeric materials.

The results reported in this thesis exploit well known behaviour and reactivity of siloxanes, as well as explore less well understood reactions in silicone synthesis and modification. Through innovative manipulation of these systems, we have achieved new levels of control in siloxane materials. Future work will continue to build on these themes.