



ELSEVIER

Journal of Organometallic Chemistry 572 (1999) 37–47

Journal  
of Organo  
metallic  
Chemistry

# Synthesis of $^{14}\text{C}$ -labeled cyclic and linear siloxanes

Sudarsanan Varaprath \*

*Dow Corning Corporation, Health and Environmental Sciences, DC-3, Mail # CO 3101, 2200 W. Salzburg Road, Auburn, MI 48686-0994 USA*

Received 19 March 1998; received in revised form 5 August 1998

## Abstract

Simple procedures to synthesize a variety of  $^{14}\text{C}$ -labeled monomeric and polymeric siloxanes are described. Specifically, the synthesis of the following siloxanes, some of which are of significant commercial importance are provided:  $^{14}\text{C}$ -octamethylcyclotetrasiloxane ( $\text{D}_4$ ),  $^{14}\text{C}$ -decamethylcyclopentasiloxane ( $\text{D}_5$ ),  $^{14}\text{C}$ -hexamethyldisiloxane (MM),  $^{14}\text{C}$ -dimethyldimethoxysilane and  $^{14}\text{C}$ -dimethylsilanediol (DMSD) are examples of discrete monomeric species.  $^{14}\text{C}$ -350 and 1000 cSt polydimethylsiloxanes (PDMS) are examples of polymeric species. Synthesis of the monomeric species with the exception of dimethylsilanediol involve reactions of Grignard reagents with the appropriate chlorosilanes, while the polymeric materials were synthesized via acid catalyzed equilibration reaction of  $^{14}\text{C}$ - $\text{D}_4$  with dodecamethylpentasiloxane ( $\text{MD}_3\text{M}$ ). The compound  $^{14}\text{C}$ -DMSD was obtained by the hydrolysis of  $^{14}\text{C}$ -dimethyldimethoxysilane. The labeled materials listed here were synthesized for their utility as tracers in several of the ongoing environmental fate and effects studies as well as toxicological investigations. © 1999 Elsevier Science S.A. All rights reserved.

**Keywords:**  $^{14}\text{C}$ -labeled siloxanes; Siloxanes; Grignard reagent

## 1. Introduction

Silicones are endowed with outstanding properties such as high thermal stability, weather resistance, hydrophobicity, resistance to heat and cold, dielectric properties, film forming abilities, surface activity, release and lubrication properties, etc. rendering them invaluable in a wide variety of industrial and consumer product applications. There are literally thousands of polydimethylsiloxane based products that find applications in electrical, construction, rubber, plastic, glass, textile, leather, pharmaceutical, cosmetic, etc. industries [1]. Certain cyclic siloxanes such as octamethylcyclotetrasiloxane ( $\text{D}_4$ <sup>1</sup>) and decamethylcyclopentasiloxane ( $\text{D}_5$ ) are also of significant commercial importance.  $\text{D}_4$  and  $\text{D}_5$ , for example, which are produced in hundreds

of millions of pounds a year globally, are key ingredients in a variety of personal care product formulations that include antiperspirants, colognes hair sprays, etc.  $\text{D}_4$  in particular is also a critical intermediate in the production of silicone polymers which in turn find use in numerous applications such as building sealants, rubber products, fabric coatings, etc.

During its widespread application in consumer applications, siloxane monomers such as  $\text{D}_4$ ,  $\text{D}_5$  and certain polymers of specific viscosities (350 and 1000 cSt) are being subjected to a number of environmental fate and effects studies, as well as toxicological testing [2–6]. Aquatic and environmental fate testing on  $\text{D}_4$  for example has been the focus of a TSCA Section 4 Consent Order in 1988 [7]. These studies often require the use of radiolabeled materials in order that their distribution either as the parent or degradation products in biological or environmental systems be conveniently monitored.

This paper describes procedures to synthesize a few of these important siloxane monomers that are  $^{14}\text{C}$ -la-

\* Tel.: +1 517 4964795; fax: +1 517 4965595.

<sup>1</sup> General electric siloxane notation is as follows: M =  $\text{Me}_2\text{SiO}-$ ; D =  $-\text{OMe}_2\text{SiO}-$ ; T =  $\text{MeSiO}_{3/2}$ ; Q =  $\text{SiO}_{4/2}$ .

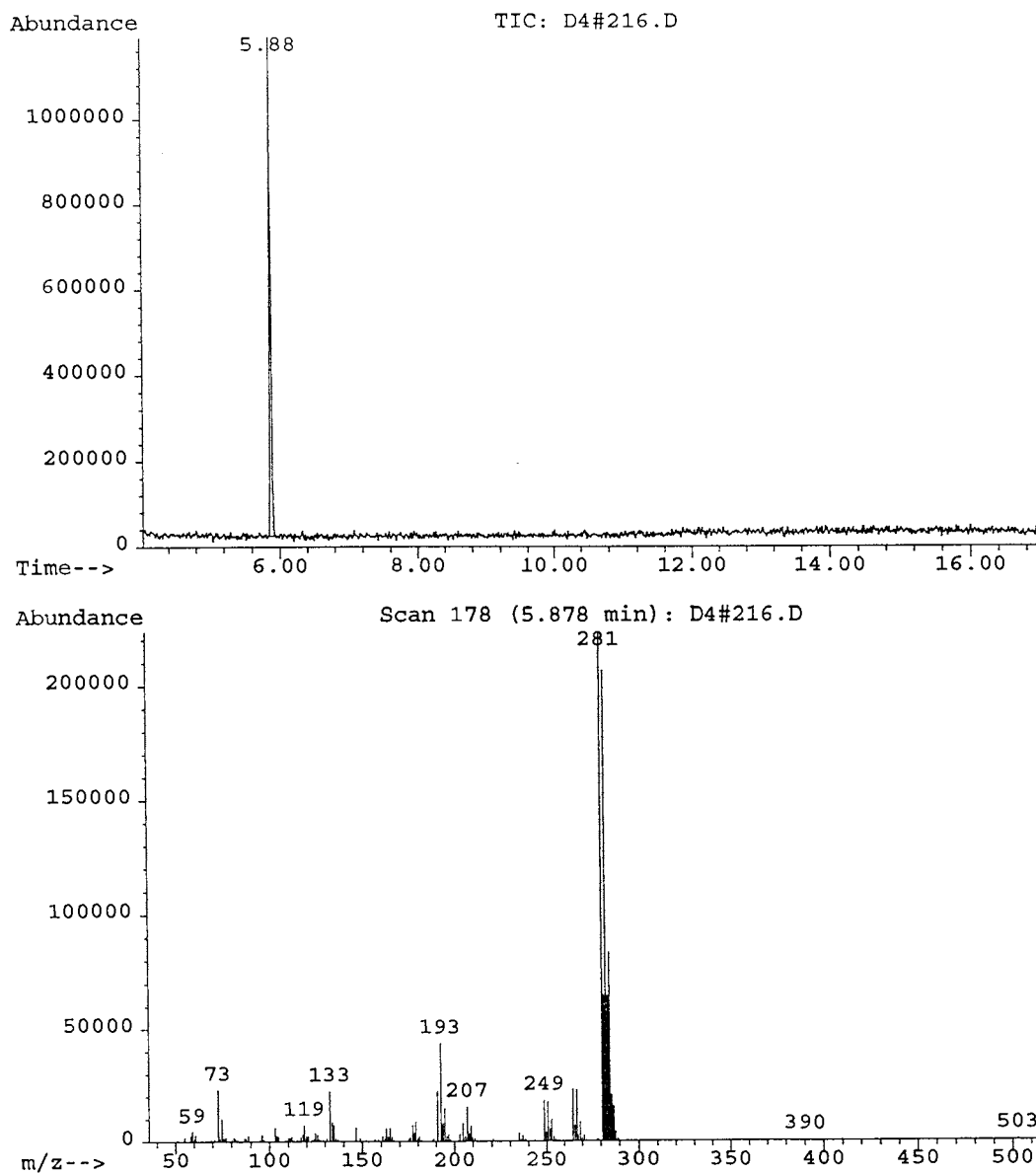


Fig. 1. GC-MS of  $^{14}\text{C}$ -octamethylcyclotetrasiloxane ( $\text{D}_4$ ).

beled, and the utility of the latter in synthesizing polymers of various molecular sizes.

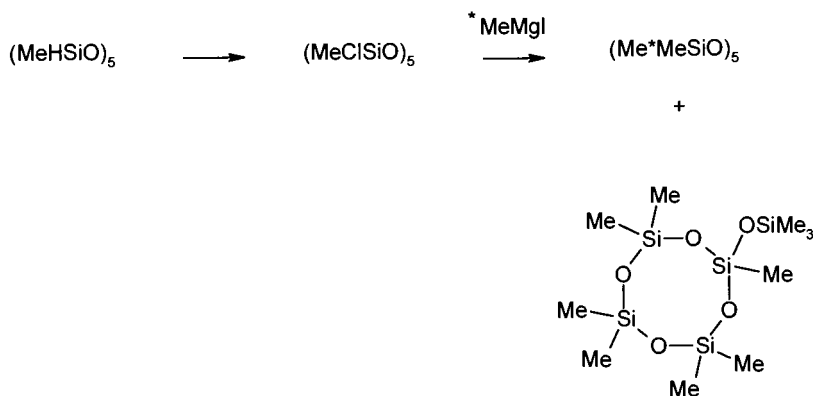
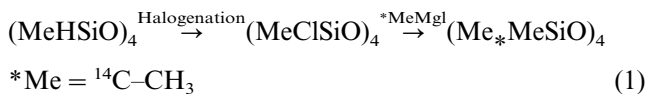
## 2. Results and discussion

### 2.1. Synthesis of $^{14}\text{C}$ - $\text{D}_4$

Among the cyclic siloxanes,  $\text{D}_4$  ranks high in consumer product applications. It is also the preferred monomeric species for industrial production of siloxane polymers. These usage prompted the environmental, and toxicological studies and thus the need for  $^{14}\text{C}$ - $\text{D}_4$  arose. The monomeric  $^{14}\text{C}$ - $\text{D}_4$  also served as an excellent intermediate for synthesizing a variety of linear polymeric siloxanes. An added feature of

$^{14}\text{C}$ - $\text{D}_4$  is that the polymerization can be conducted using solid support acidic catalyst such that the polymers will have none of or very minimal silanol contaminant. Absence of silanols is in essence a pre-requisite for labeled polymers, since the very silanols are the end products often sought in environmental degradation [8–12] and metabolism [13] studies. This requirement thus excluded the utility of precursors such as  $^{14}\text{C}$ -labeled  $\text{Me}_2\text{SiX}_2$ , (where X = halides or alkoxy functions) for polymer synthesis since formation of the silanol terminated polymers cannot be avoided.

The selected synthetic sequence for the  $^{14}\text{C}$ - $\text{D}_4$  is shown in Eq. (1) which involves halogenation of 1,3,5,7-tetramethylcyclotetrasiloxane followed by a Grignard reaction.

Scheme 1. Synthetic sequence for  $^{14}\text{C}-\text{D}_5$ .

Several reagents were evaluated for halogenation of  $(\text{MeHSiO})_4$ :  $\text{CCl}_4$  and benzoyl peroxide (BPO) [14];  $\text{CCl}_4$  and 10% Pd/C [15]; *N*-chlorosuccinimide (NCS) in chloroform and direct chlorination [16]. Use of  $\text{CCl}_4/\text{BPO}$  or  $\text{CCl}_4/\text{Pd/C}$  as reagents resulted in low conversion. With NCS,  $(\text{MeHSiO})_4$  was found to be completely consumed with the formation of the chlorinated product. It was interesting to observe that NCS reaction failed when dry chloroform (distilled over  $\text{P}_2\text{O}_5$ ) was used. However, with the addition of a trace amount of ethanol, a very exothermic reaction ensued forming the product. It is speculated that a trace amount of chlorinated product formed initially may have reacted with ethanol to generate HCl which then catalyzed the reaction. From a comparative evaluation based on yield and ease of purification and nature of by-products, it was determined that direct chlorination is the preferred method. It was found to be advantageous to conduct the reaction at lower temperatures ( $< 5^\circ\text{C}$ ) as opposed to  $20^\circ\text{C}$  [16] to prevent side chain halogenation. Also, to control the highly exothermic reaction, the chlorine gas was diluted with dry  $\text{N}_2$  or Ar gas. It was also critical to monitor the reaction for completion by GC–MS. Substitution of the first three hydrogen atoms was quite rapid. However, the substitution of the last hydrogen atom was much slower. Hence, the common assumption that the persistence of yellowish–green coloration of the reaction medium from excess chlorine as an indication of the completion of the reaction was found to be misleading. Presence of the mass  $m/z$  361 (M-15) expected of the completely substituted product, and the absence of masses corresponding to partially chlorinated product in GC–MS assured the completeness of the reaction.

The subsequent step which is the conversion of  $(\text{MeClSiO})_4$  to the methylated product was first attempted using unlabeled reagents in order that a suit-

able experimental condition is established prior to  $^{14}\text{C}$  labeling. Two organometallic reagents, MeLi and MeMgI were considered. Of these, MeLi in ether was found to be unsuitable. At  $-78^\circ\text{C}$ , the reaction generated no  $\text{D}_4$ . Although  $\text{D}_4$  was formed on warming to  $0^\circ\text{C}$  and continuing the reaction overnight, other equilibration products  $\text{D}_5$  and  $\text{D}_6$  were also being formed. Even with the mildly nucleophilic Grignard reagent, the alternative to MeLi, there was still the potential for ring opening polymerization of  $\text{D}_4$ . Therefore it was first established that  $\text{D}_4$  was stable to MeMgI in diethyl ether (a solvent of choice) at reflux temperature at least over a period of 4 days. Following this, the reaction of  $(\text{MeClSiO})_4$  with an excess of MeMgI was conducted in diethylether at room temperature (r.t.) over a 20 h period. GC–MS analysis indicated a complete conversion of  $(\text{MeClSiO})_4$  to the desired  $\text{D}_4$ . The experimental procedure was then applied for the synthesis of  $^{14}\text{C}-\text{D}_4$  allowing  $^{14}\text{C}-\text{MeMgI}$  to react with  $(\text{MeClSiO})_4$  (1.1:1 stoichiometry). The isolated yield of  $^{14}\text{C}-\text{D}_4$  by preparative GC, was 70%. The yield was based on the limiting reagent  $^{14}\text{C}-\text{MeI}$ . GC–MS analysis (Fig. 1) confirmed the product.

## 2.2. Synthesis of $^{14}\text{C}-\text{D}_5$

Unlike  $\text{D}_4$ , the utility of  $\text{D}_5$  for making polymers is limited, but it finds numerous applications in personal care industries. Again, a labeled material was needed for the same reasons cited for  $\text{D}_4$ . The synthetic scheme for  $^{14}\text{C}-\text{D}_5$  is quite similar to that of  $^{14}\text{C}-\text{D}_4$ . Starting from 1,3,5,7,9-pentamethylcyclopentasiloxane  $[(\text{MeHSiO})_5]$ , the corresponding chloro-derivative was obtained in respectable yield. But in contrast to the clean conversion of  $(\text{MeClSiO})_4$  to  $\text{D}_4$ ,  $(\text{MeClSiO})_5$  yielded in addition to the expected  $\text{D}_5$ , a rearrangement product (Scheme 1) in a 5–10% yield (Fig. 2).

This isomeric ring-contracted product identified by GC–MS analysis has an identical fragmentation pattern to  $\text{D}_5$  with some variation only in the relative

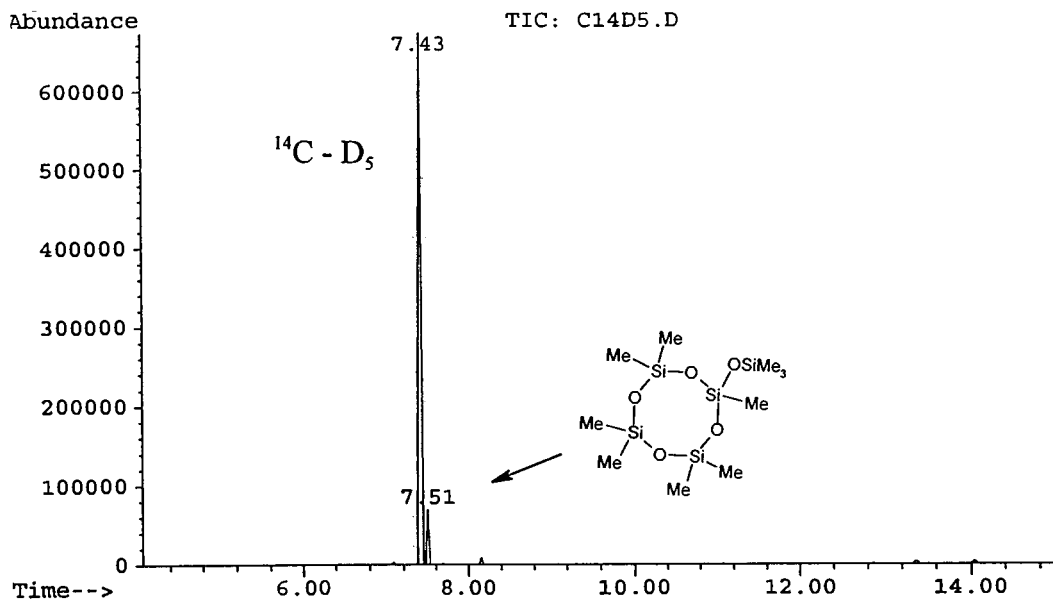
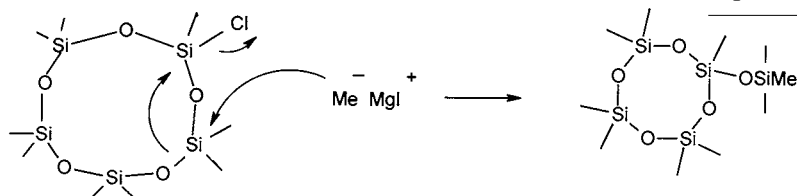


Fig. 2. GC-MS total ion chromatogram of  $^{14}\text{C}$ -decamethylcyclopentasiloxane ( $\text{D}_5$ ) showing the isomeric impurity of heptamethyltrimethylsilyloxy-cyclo-tetrasiloxane.

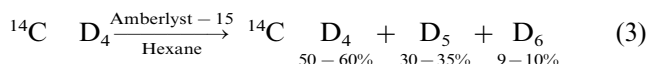
intensities of major fragments (Fig. 3). The identity was confirmed by comparison to an authentic material synthesized by an unambiguous route involving formation of heptamethylcyclotetrasiloxanol [17] and silylating the latter with bis(trimethylsilyl)trifluoroacetamide. The mechanistic path for the formation of this isomer was not clearly established. One of the possibilities is shown in Eq. (2).



The undesired isomer is not being formed from possible impurities in the starting  $(\text{MeHSiO})_5$ , since the latter, fractionated by spinning band distillation, is of extremely high purity (99.9%). A variety of experimental conditions that included changes in reaction medium, temperature, and the organometallic reagents were attempted, but the formation of the isomeric impurity could not be avoided. It was of interest to note that with  $\text{MeLi}$  as the organometallic reagent, the relative ratios actually reversed, the isomeric impurity now being formed in higher percentage.

Since the protocols of certain toxicological investigations mandated that this impurity be totally absent, attempts were made to isolate the impurity by HPLC and preparative GC (using a packed column). The method was found to be impractical and therefore an

alternative route (Eq. (3)), was developed for such special applications.



Accordingly,  $^{14}\text{C}$ - $\text{D}_4$  obtained from the cyclic chlorosilane precursor (Eq. (1)) was subjected to equilibration for 4 h at reflux temperature in hexane in presence of the acid catalyst Amberlyst-15<sup>®</sup> (an ion-exchange resin). No trace of the isomeric impurity was seen by GC-MS. Only the expected  $^{14}\text{C}$ - $\text{D}_5$  and the equilibration products,  $^{14}\text{C}$ - $\text{D}_4$



and  $^{14}\text{C}$ - $\text{D}_6$  were formed (Fig. 4).  $^{14}\text{C}$ - $\text{D}_5$  was readily isolated from the mixture by preparative GC. The by products  $^{14}\text{C}$ - $\text{D}_4$  and  $^{14}\text{C}$ - $\text{D}_6$  were re-equilibrated to obtain more of the desired material.

### 2.3. Synthesis of $^{14}\text{C}$ -hexamethyldisiloxane (MM)

Hexamethyldisiloxane, a siloxane that is manufactured in commercial quantities is often used as a silylating agent in organic synthesis and also as an end capping unit polymerization reactions. The  $^{14}\text{C}$ -labeled moiety was synthesized from the readily available 1,3-dichlorotetramethyldisiloxane by reacting the latter with  $^{14}\text{C}$ -labeled methyl magnesium iodide in diethyl ether. Again, no siloxane bond cleavage was observed. The product (Fig. 5) was obtained pure by preparative GC following sample work up.

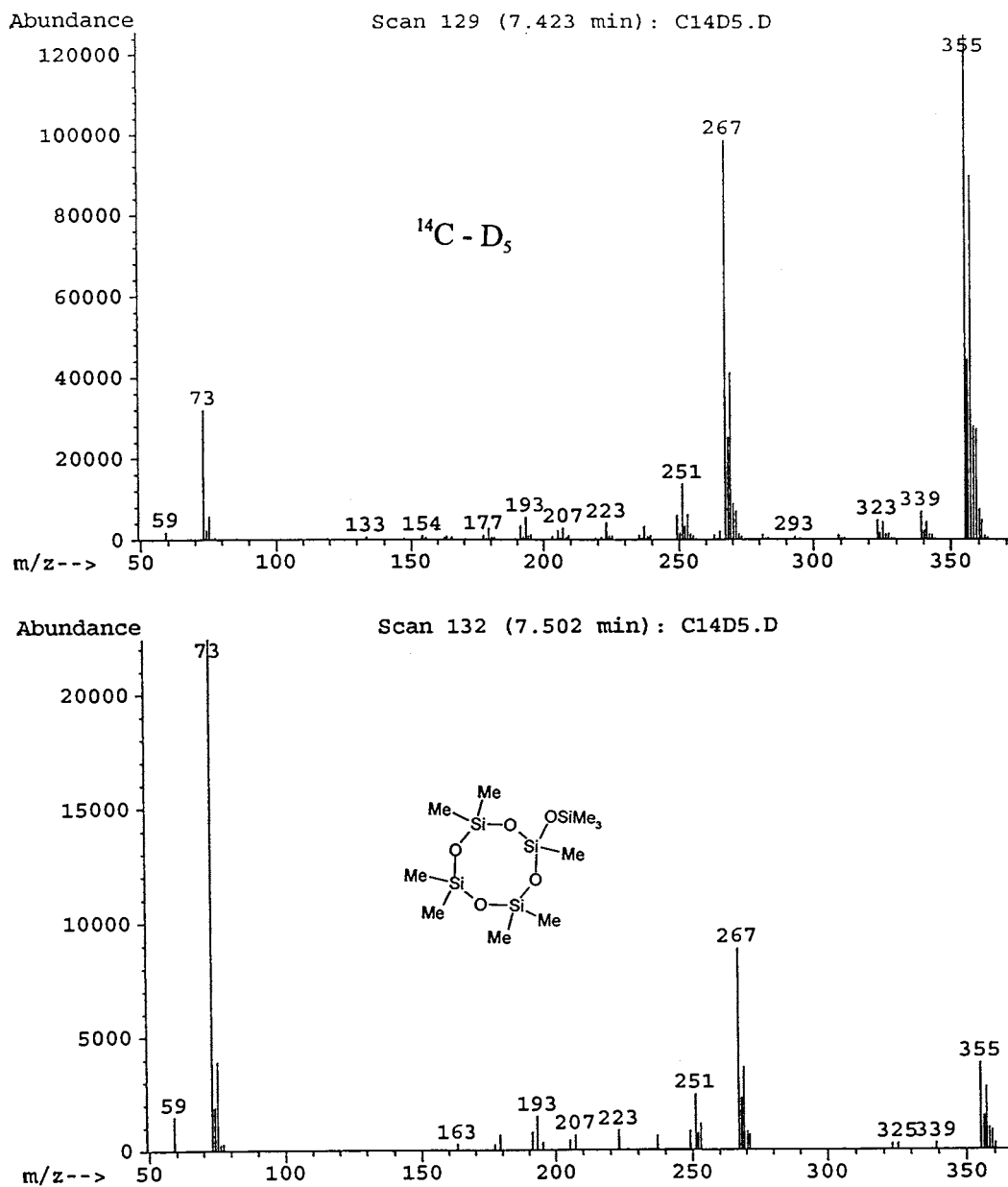
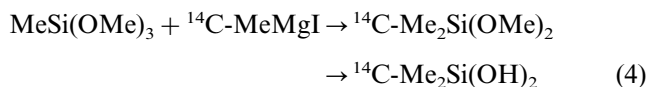


Fig. 3. GC-MS fragmentation pattern showing the similarity of  $^{14}\text{C}$ -decamethylcyclopentasiloxane and heptamethyltrimethylsilyloxycyclotrisiloxane.

#### 2.4. Synthesis of $^{14}\text{C}$ -dimethylsilanediol (DMSD)

Dimethylsilanediol  $\text{Me}_2\text{Si}(\text{OH})_2$  is a key environmental as well as a bio degradation product of linear and cyclic dimethylsiloxanes. In the environmental arena, PDMS entering into waste water treatment plants from consumer application gets adsorbed onto sludges [18,19]. When the latter is applied as fertilizers, PDMS comes into contact with soil. There it degrades primarily to DMSD [8–11]. Degradation of (cyclic) PDMS to DMSD is also known in animal metabolism [13]. Availability of  $^{14}\text{C}$ -labeled DMSD can make it convenient to monitor its formation and subsequent degradation to  $\text{CO}_2$  using HPLC equipped with a radioisotope detector.

The synthetic route for  $^{14}\text{C}$ -dimethylsilanediol via the intermediate  $^{14}\text{C}$ -dimethyldimethoxysilane is shown in Eq. (4).



Reaction of methyltrimethoxysilane with an equivalent of  $^{14}\text{C}$ -labeled Grignard reagent yielded  $^{14}\text{C}$ -dimethyldimethoxysilane. The latter was isolated pure by preparative GLC.

Being unstable in pure isolated form [20], it is preferable to prepare  $^{14}\text{C}-\text{Me}_2\text{Si}(\text{OH})_2$  as an aqueous solution of desired concentration. This was done by simply

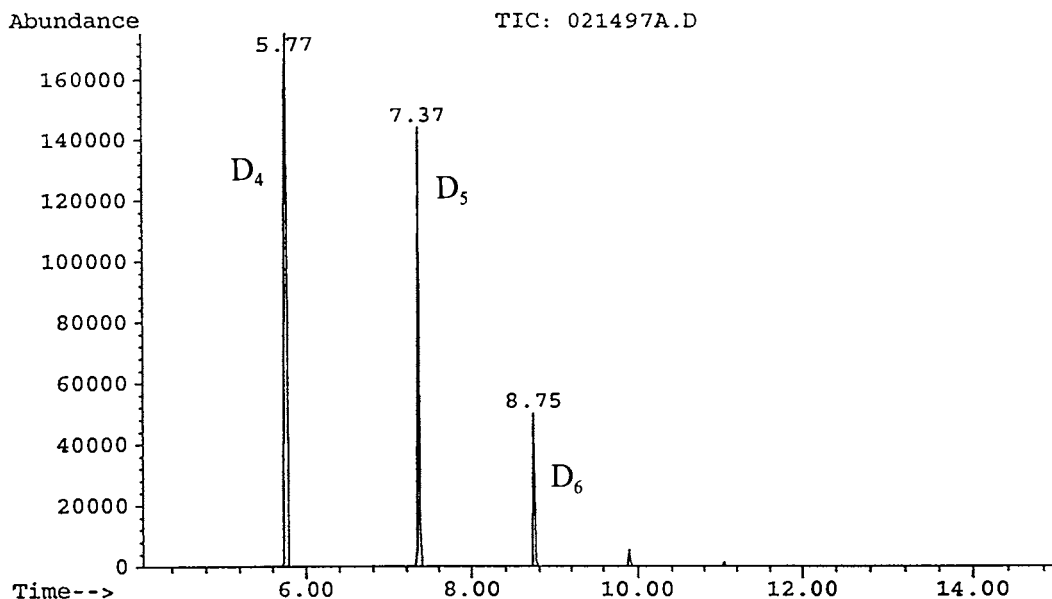


Fig. 4. GC-MS total ion chromatogram showing the products from the acid catalyzed the equilibration  $D_4$ .

adding known amounts, of  $^{14}\text{C-Me}_2\text{Si(OMe)}_2$  (amount determined based on specific activity and the concentration needed) to pure water (milli-Q<sup>TM</sup> water) taken in teflon bottles. The  $^{14}\text{C-Me}_2\text{Si(OMe)}_2$  compound readily hydrolyzes to the desired  $^{14}\text{C-Me}_2\text{Si(OH)}_2$  within minutes at r.t. The structure was confirmed by GC-MS (Fig. 6) analysis.

The method described for DMSD here is complementary to the procedure reported [21] in the literature, where  $^{14}\text{C}$ -labeled diphenyldimethylsilane was first converted to dimethyldichlorosilane and the latter then hydrolyzed in presence of an acid scavenger. The current method, however, is valuable in situations requiring strictly neutral conditions for its preparation.

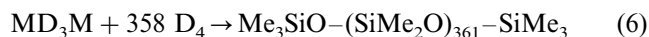
### 2.5. Synthesis of polydimethylsiloxane polymers

To synthesize polydimethylsiloxane polymers, the approach was to subject  $^{14}\text{C}$ -labeled  $D_4$  to acid catalyzed ring opening polymerization in presence of end-capping siloxane—the latter providing the trimethylsilyl groups at the end of the polymer chain. Dodecamethylpentasiloxane ( $\text{MD}_3\text{M}$ ) was chosen for end capping, since it was available in extremely high purity. For the catalyst, solid-supported strongly acidic Amberlyst-15<sup>®</sup> was chosen since it was easier to remove it at the end of the reaction simply by filtration and neutralization can be avoided.

In order that certain viscosities are attained for the polymers, the relative ratios of the  $D_4$  and the end capping siloxane moieties must be adjusted precisely. The equation relating viscosity and the number of 'D' units (Eq. (5)) provided a rough estimate of the ratio as a starting point.

$$\text{Log } \eta = 0.1 \sqrt{n + 1.1} \quad (5)$$

where  $\eta$  is the viscosity at 25°C, and  $n$  is the number of  $\text{Me}_2\text{SiO}$  units. For synthesizing a 1000 cSt viscosity PDMS fluid for example,  $n$  was calculated to be 361. Taking into account the 3 'D' units to be provided by  $\text{MD}_3\text{M}$ , the stoichiometry on the molar basis is then given as follows (Eq. (6)):



Several equilibrium reactions with formulations centered around the stoichiometry shown in the above equation was set up using unlabeled materials. The formulation that consistently gave polymers of the targeted viscosity and  $M_n$  (number average molecular weight as determined by size exclusion chromatography) was then selected and applied to prepare the  $^{14}\text{C}$ -labeled polymer (see experimental for the stoichiometry).  $^{14}\text{C-D}_4$  (in amounts determined based on the specific activity requirement for the polymer) was mixed with sufficient quantities of unlabeled  $D_4$  as required per Eq. (6). Low molecular weight species generated at equilibrium in this acid catalyzed polymerization were removed at low pressure by stripping at 150°C over ca. 16 h. With this procedure the labeled polymers of 350 and 1000 cSt viscosities were prepared in yields of 87 and 85%, respectively.

The average viscosities for the synthetic 350 and 1000 cSt PDMS fluids were 362 and 978, respectively. The corresponding viscosities for reference materials were 360 and 1054. The synthetic polymers were also characterized by size exclusion chromatography. The GPC profiles obtained for the synthetic materials were in good agreement with authentic commercial products (Figs. 7 and 8).

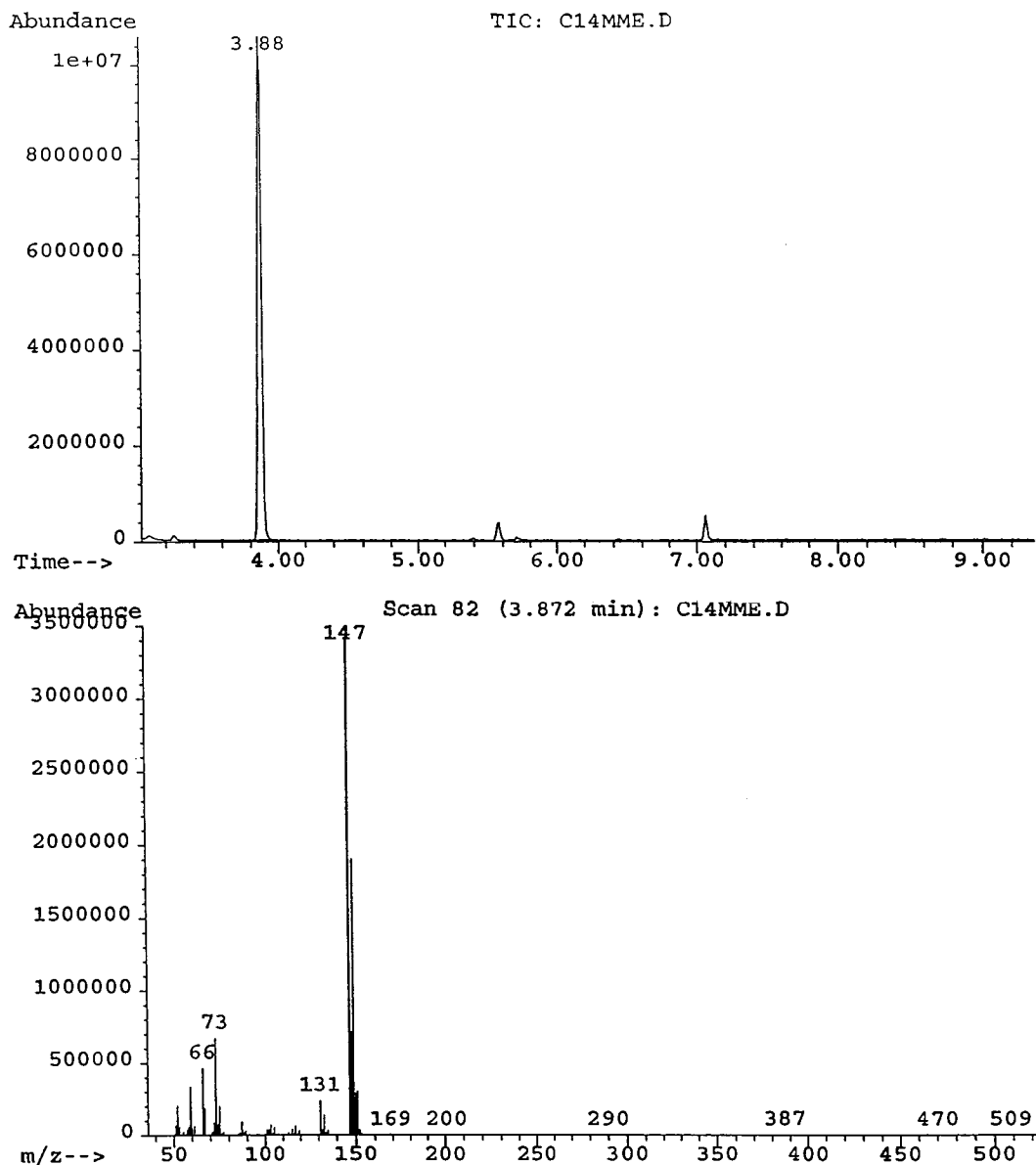


Fig. 5. GC-MS of  $^{14}\text{C}$ -hexamethyldisiloxane.

In principle, with this route polymers of any desired viscosity (molecular weight) can be synthesized. But, as the molecular weight of the polymers increase, the amount of the end capping moiety  $\text{MD}_3\text{M}$  needed relative to  $\text{D}_4$  will be considerably less. Precision in weighing it ( $\text{MD}_3\text{M}$ ) can become a limiting factor. However, in these instances siloxanes of molecular weight much higher than  $\text{MD}_3\text{M}$  must be used.

One of the  $^{14}\text{C}$ -labeled polymer (350 cSt PDMS) synthesized by the current procedure was tested for its stability over a 2 year period. It is well known that presence of acids or bases can affect depolymerization of siloxane polymers [2–4]. Since during the synthesis, the  $^{14}\text{C}$ -labeled PDMS was thoroughly

devolatilized by heating the material under reduced pressure ( $150^\circ\text{C}$ , 0.1 mmHg), low molecular weight PDMS oligomers having boiling points lower than  $400^\circ\text{C}$  at atmospheric pressure (760 mmHg) were absent. If, however, they are being formed due to depolymerization, their presence would be noticeable in HPLC analysis. A total of 2 years following the synthesis of the  $^{14}\text{C}$ -labeled 350 cSt PDMS, the same batch was dissolved in THF as before and analyzed by HPLC under the same conditions. The molecular weight distribution was identical to that of 2 years previously, showing that the PDMS synthesized by the current method had been stable during that 2 year period.

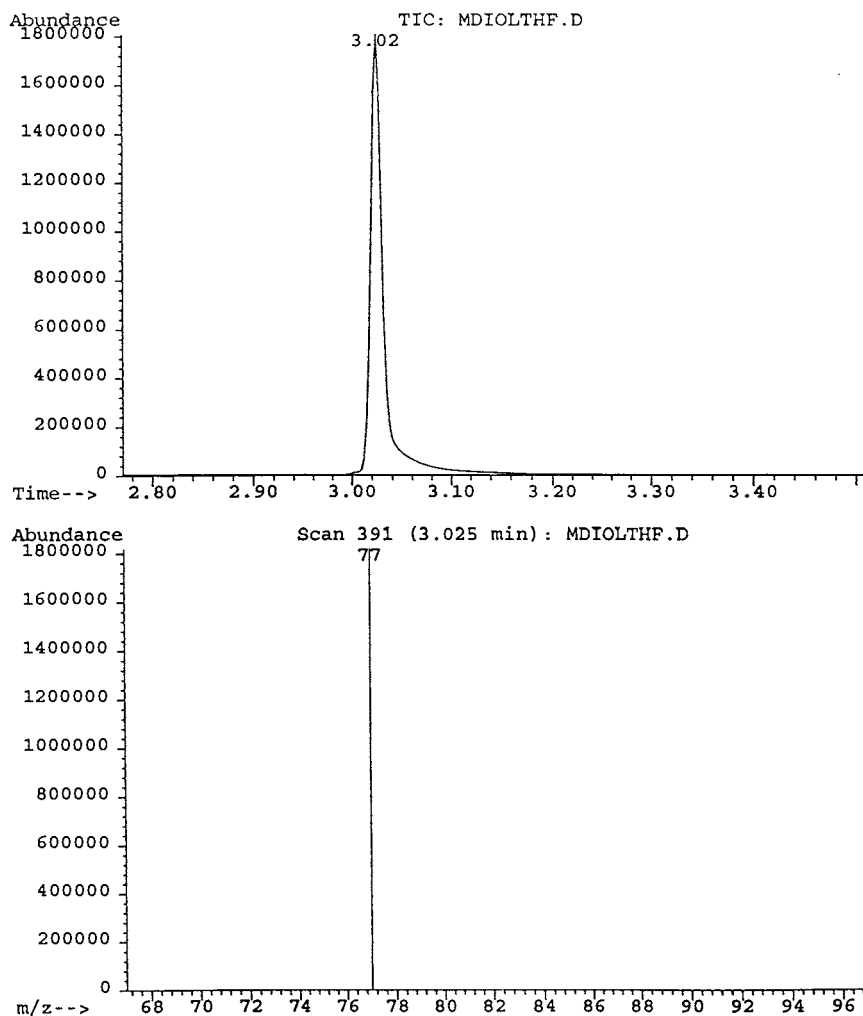


Fig. 6. GC-MS (SIM) spectra of  $^{14}\text{C}$ -dimethylsiloxanediol (DMSD).

### 3. Experimental

#### 3.1. Materials

Dodecamethylpentasiloxane (i.e. MD<sub>3</sub>M, a Dow Corning<sup>®</sup> 2 cs 200 fluid) was of purity greater than 99.5%. Octamethylcyclotetrasiloxane of 99.5% initial purity obtained from General Electric (SF1173 fluid) was further distilled to obtain essentially an 100% pure material. Amberlyst-15 acidic ion exchange resin, methylithium (3 M solution in diethyl ether), methylmagnesium iodide (3 M solution in diethyl ether), carbon tetrachloride and hexane were purchased from Aldrich Chemical Co. Carbon tetrachloride was distilled over phosphorus pentoxide before use. 1,3,5,7-Tetramethylcyclotetrasiloxane [(MeHSiO)<sub>4</sub>] and pentamethylcyclopentasiloxane [(MeHSiO)<sub>5</sub>] were purchased from Gelest, Inc. The compound (MeHSiO)<sub>4</sub> was used as such without further purification, (MeHSiO)<sub>5</sub> was purified by spinning band distillation prior to use. Chlorine gas (1 lb. lecture bottle) was purchased from

Michigan Air gas. For reference 350 and 1000 cSt PDMS fluids, commercial Dow Corning<sup>®</sup> fluids were used.

#### 3.2. Instrumentation

GC/MS was performed using Hewlett Packard 5890 series II Gas Chromatograph coupled with either HP 5989A Mass Spectrometer or 5970 B MSD, a HP 7673 GC/SFC injector, and an electronic pressure control system. Data analysis was performed using a Windows<sup>®</sup> based Chem Station.

Viscosity measurements were made using Cannon-Zeit-Fuchs Viscometer (Viscometer # Y625). Specific activities of  $^{14}\text{C}$ -labeled materials were determined using TM Analytic, Model 5303 Mark V, Liquid Scintillation Counting System (Packard), and 2500 TR Liquid Scintillation Counter (Packard). Gel Permeation Chromatography was performed using Waters Programmable pump (model # 590), an autosampler (Waters 712 WISP), a differential Refractometer (Wa-



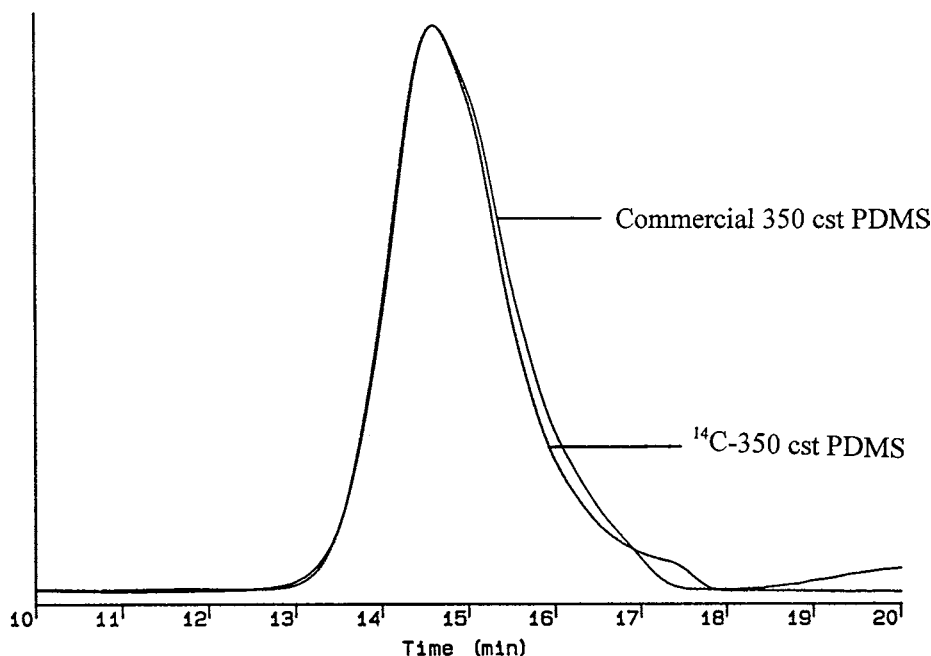


Fig. 7. Overlay of size exclusion chromatograms of synthetic  $^{14}\text{C}$ -labeled and commercial 350 cst polydimethylsiloxane.

ters 410), and Ultrastyrigel column (Waters). GPC column parameters were as follows: Polymer Lab Series C column of dimension  $2 \times 30$  cm; Toluene was used as the mobile phase at a flow rate of  $1 \text{ ml min}^{-1}$ .

### 3.3. Synthesis of $(\text{MeClSiO})_4$

Carbon tetrachloride (250 ml; distilled over  $\text{P}_2\text{O}_5$  and dried over anhydrous  $\text{Na}_2\text{SO}_4$ ) and 1,3,5,7-tetramethylcyclotetrasiloxane (50 ml) were placed into a dry 500 ml three necked flask equipped with gas dispersion tube, a thermometer and a water condenser. The gas dispersion tube was connected to a lecture bottle of chlorine gas via a Teflon lined stainless steel flexible hose fitted with ultratorr fittings (from Cajon). The top of the condenser is connected via a 'Y' tube to an Argon gas cylinder and a bubbler containing 350 cs PDMS.

The solution was degassed and saturated with argon. While continuing to pass argon gently, the flask was cooled in acetone bath to about  $0^\circ\text{C}$  by the addition of Dry Ice. Chlorine gas was then passed through the gas dispersion tube placed well immersed in the reaction medium. The reaction temperature was maintained at  $5\text{--}10^\circ\text{C}$  by intermittent addition of Dry Ice to an acetone bath. In general, keeping the acetone bath at  $0^\circ\text{C}$  was found to maintain the reaction temperature at less than  $10^\circ\text{C}$ .

When the greenish yellow color of the chlorine gas persisted in the solution indicating that the reaction is nearing completion, monitoring by GC-MS analysis was started. Chlorination was continued until, in GC-MS, all the partial chlorination products (i.e. M-15 ions

$m/z$  259, 293 and 327 of mono, di and tri substituted products) disappeared and the completely chlorinated product (ion 361) appeared. The retention time for the fully chlorinated product was around 7.96 min at the following GC conditions: oven at  $70^\circ\text{C}$ , 3 min hold, heating rate  $20^\circ\text{C min}^{-1}$ , final temperature  $210^\circ\text{C}$ , 5 min hold; cross linked 5% PhMe siloxane column (HP-5 MS) of dimensions:  $30 \times 0.25 \times 0.025 \mu\text{m}$  film thickness.

At the completion of the reaction, the mixture was transferred under an argon atmosphere into a dry 500 ml one necked-flask. Most of the solvent was removed using a rotary evaporator at  $<40^\circ\text{C}$  (60–80 mmHg aspirator pressure). A tube containing Drierite was placed between the water aspirator and the rotary evaporator to prevent moisture entering the system. The reaction mixture was then transferred (inside of a glove bag) into a 250 ml one-necked 14/20 round bottomed flask and the product distilled under low pressure (0.01 mmHg,  $67\text{--}70^\circ\text{C}$ ). The yield was 70% (55 g).

### 3.4. Synthesis of $(\text{MeClSiO})_5$ [17]

Using 50 g of 1,3,5,7,9-pentamethylcyclopentasiloxane and following the procedure described for  $(\text{MeClSiO})_4$ , the fully chlorinated product  $(\text{MeClSiO})_5$  was synthesized. The M-15 ion of  $m/z$  455 was monitored by GC-MS for the product. GC-MS showed the presence of three isomers at 9.66, 9.82 and 9.92 min under the same GC conditions of  $(\text{MeClSiO})_4$ . The product was obtained in a 78% (58.3 g) yield.

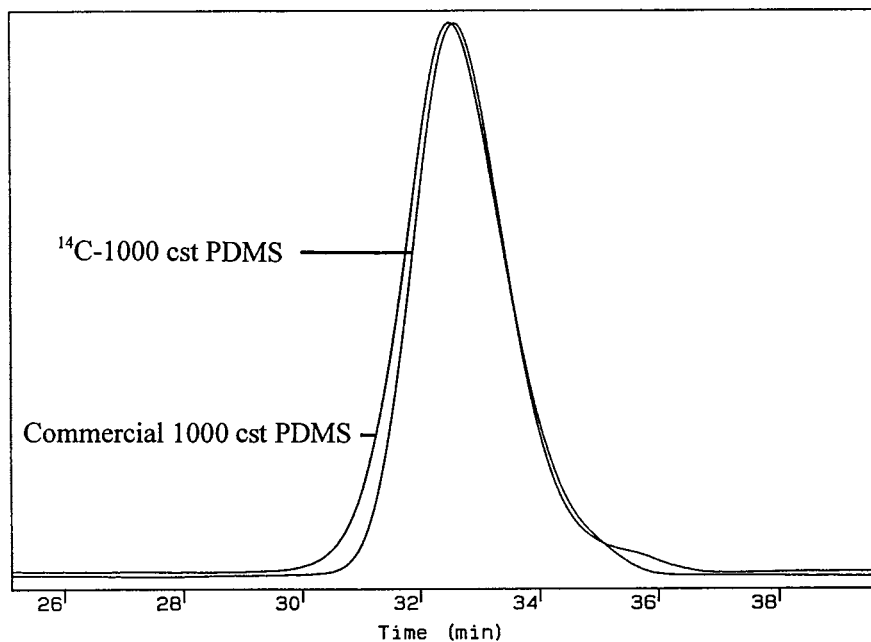


Fig. 8. Overlay of size exclusion chromatograms of synthetic  $^{14}\text{C}$ -labeled and commercial 1000 cSt polydimethylsiloxane.

### 3.5. Synthesis of $^{14}\text{C}\text{-D}_4$

Magnesium powder (4.4 mmol) was placed in a three-necked flask equipped with a magnetic stir bar, an addition funnel, and a condenser which in turn was fitted with a  $\text{N}_2$  gas inlet tube. Dry diethylether (2 ml) was added. Under a blanket of  $\text{N}_2$ ,  $^{14}\text{CH}_3\text{I}$  (4.4 mmol) was added drop wise. An exothermic reaction ensued. Addition of  $^{14}\text{CH}_3\text{I}$  was continued at a rate to maintain a gentle reflux.

To the freshly prepared Grignard reagent, tetra(methylchloro)cyclotetrasiloxane (1 mmol) dissolved in 2 ml of ether was added. After the addition was over, the reaction mixture was heated overnight in an oil bath maintained at  $45^\circ\text{C}$ . The flask was cooled to r.t. and the contents quenched with cold water. The ether layer was separated, washed with cold water until wash water is neutral. Pure  $\text{D}_4$  was collected using preparative GC. The isolated yield was 60% based on  $^{14}\text{CH}_3\text{I}$ . The specific activity of the product was determined to be  $47 \text{ mCi mmol}^{-1}$ . The radiochemical purity as determined by gas chromatography was 99.9%.

### 3.6. Synthesis of $^{14}\text{C}\text{-D}_5$

#### 3.6.1. Method A

Using 1 mmol of penta(methylchloro)cyclopentasiloxane and 5.5 mmol of freshly prepared  $^{14}\text{CH}_3\text{MgI}$ ,  $^{14}\text{C}\text{-D}_5$  was synthesized following the procedure described for  $^{14}\text{C}\text{-D}_4$ . The product purified by preparative GC was obtained in a 35% yield based on  $^{14}\text{CH}_3\text{I}$ . The specific activity of the product was determined to be

$30.6 \text{ mCi mmol}^{-1}$ . The radiochemical purity as determined by gas chromatography is  $> 99\%$ .

#### 3.6.2. Method B

The  $^{14}\text{C}\text{-D}_4$  compound purified by preparative GC (1 mmol) and catalytic amount of Amberlyst-15 was heated at reflux temperature in hexane for 4 h. Pure  $^{14}\text{C}\text{-D}_5$  was collected by preparative GC method. The  $^{14}\text{C}\text{-D}_4$ , and  $^{14}\text{C}\text{-D}_6$  that were also collected by preparative GC were re-equilibrated in hexane to obtain additional quantities of  $^{14}\text{C}\text{-D}_4$ . Based on  $^{14}\text{C}\text{-D}_4$  and one recycling process, the collective yield was 30%. The specific activity of the product was determined to be  $22 \text{ mCi mmol}^{-1}$ . The radiochemical purity as determined by gas chromatography is  $> 99\%$ .

### 3.7. Synthesis of $^{14}\text{C}\text{-MM}$

Using 1 mmol of 1,3-dichlorotetramethyldisiloxane and 2.2 mmol of freshly prepared  $^{14}\text{C}\text{-MeMgI}$ ,  $^{14}\text{C}\text{-MM}$  was synthesized following the procedure described for the synthesis of  $^{14}\text{C}\text{-D}_4$ . The product purified by preparative GC was obtained in a 40% yield based on  $^{14}\text{CH}_3\text{I}$ . The specific activity of the product was determined to be  $24.4 \text{ mCi mmol}^{-1}$ . The radiochemical purity as determined by gas chromatography was 98%.

### 3.8. Synthesis of $^{14}\text{C}\text{-Me}_2\text{Si(OH)}_2$

The  $^{14}\text{C}\text{-Me}_2\text{Si(OH)}_2$ , being unstable in pure solid form, was prepared as an aqueous solution of desired

concentration. For obtaining an 100 ppm aqueous solution, 15  $\mu\text{l}$  of  $^{14}\text{C-Me}_2\text{Si(OMe)}_2$  was added to 100 ml of pure water (milli-Q water) taken in a 4 oz teflon bottle. The contents were stirred for 2 h to complete the hydrolysis. The specific activity of the product was determined to be  $2.5 \mu\text{Ci ml}^{-1}$ . The radiochemical purity as determined by HPLC was 95%.

### 3.9. Synthesis of polydimethylsiloxane polymers

#### 3.9.1. C-14 Labeled PDMS of 350 cSt

$^{14}\text{C-D}_4$  (25 mCi, of specific activity  $1.48 \text{ mCi mmol}^{-1}$ , purchased from Wizard Laboratories, West Sacramento, CA) was placed in a 200 ml, one-necked round-bottom flask. Pure  $\text{D}_4$  was added to the flask in an amount to make the total weight of  $\text{D}_4$  to 50.0 g.  $\text{MD}_3\text{M}$  (1.625 g) and Amberlyst-15 (0.665 g) were then placed in the flask. The flask was equipped with a water condenser. The top of the condenser was in turn fitted with a 'Drierite' moisture trap. The contents of the flask were gently stirred using a magnetic stir bar and the flask was heated for 24 h in an oil bath kept at  $100^\circ\text{C}$ . Heating was stopped at the end of this period and the flask cooled to ambient temperature.

The viscous fluid in the flask was diluted with 60 ml of reagent grade dichloromethane, and filtered through a Whatman # 1 filter paper to remove the solid acid catalyst. The filtrate was collected into a clean 250 ml flask. The original flask and the filter paper were thoroughly rinsed with fresh solvent to insure complete transfer of the PDMS fluid.

Most of the volatiles were removed using a rotary evaporator at  $90^\circ\text{C}$  under aspirator pressure (60–80 mmHg). Removal of the remaining volatiles was accomplished by low pressure distillation at  $150^\circ\text{C}$ , 0.01 mmHg for 48 h. At the end of this period, the distillation was stopped and the flask cooled to r.t. The product, obtained as a clear fluid, weighed 45 g (87% yield). The specific activity of the product was determined to be  $0.52 \text{ mCi g}^{-1}$ , and the viscosity was  $362.4 \pm 0.21 \text{ cSt}$ .

#### 3.10. C-14 Labeled PDMS of 1000 cSt

The  $^{14}\text{C}$ -labeled 1000 cSt PDMS was prepared following the procedure described for 350 cSt PDMS fluid with the following exception. At the end of the reaction, pentane rather than dichloromethane was used as the diluent. The ingredients were as follows:  $^{14}\text{C-D}_4$  (1.14 g of specific activity  $6.5 \text{ mCi mmol}^{-1}$  from Wizard Laboratories, West Sacramento, CA)  $\text{MD}_3\text{M}$  (1.34 g); unlabeled pure  $\text{D}_4$  (68.86 g); Amberlyst-15 (0.93 g). The product was obtained in an 85% yield (60.3 g). The specific activity was determined to be  $0.302 \text{ mCi g}^{-1}$  and the viscosity was 976.7 cSt.

## References

- [1] G. Koerner, M. Schulze, J. Weis (Eds.), *Silicones: Chemistry and Technology*, Vulkan-Verlag, Essen, Germany, 1991.
- [2] J.F. Hobson, Existing chemical testing for environmental fate and effects under TSCA Section 4: a case study with octamethylcyclotetrasiloxane (OMCTS), *Environ. Toxicol. Chem.* 14 (1995) 1635.
- [3] R. Grau, Octamethylcyclotetrasiloxane (OMCTS) prolonged toxicity (14 days) to rainbow trout in a flow-through test. TSCA Docket OPTS-42071B. Toxic substances Control Act Public Docket Office, Washington, DC, 1991.
- [4] J.V. Sousa, P.C. McNamara, A.E. Putt, et al., Effects of octamethyl-cyclotetrasiloxane (OMCTS) on fresh water and marine organisms, *Environ. Toxicol. Chem.* 14 (1995) 1639.
- [5] D.J. Kent, P.C. McNamara, A.E. Putt, J.F. Hobson, E.M. Silberhorn, M. Eric, Octamethylcyclotetrasiloxane in aquatic sediments: toxicity and risk assessment, *Ecotoxicol. Environ. Saf.* 29 (1994) 372.
- [6] P.H. Fackler, E. Dionne, D.A. Hartlet, J.L. Hamelink, Bioconcentration by fish of a highly volatile silicone compound in a totally enclosed aquatic exposure system, *Environ. Toxicol. Chem.* 14 (1995) 1649.
- [7] Interagency Testing Agency. 1984. Fifteenth report to the administrator. TSCA docket OPTS-42071A (1988). *Fed. Reg.* 49:46931–46949.
- [8] R.G. Lehmann, S. Varaprath, C.L. Frye, Fate of silicone degradation products (silanols) in soil, *Environ. Toxicol. Chem.* 13 (1994) 1753.
- [9] J.C. Carpenter, J.A. Cella, S.B. Dorn, A study of the degradation of polydimethylsiloxanes on soil, *Environ. Sci. Technol.* 29 (1995) 864.
- [10] R.G. Lehmann, S. Varaprath, R.B. Annelin, J. Arndt, Degradation of silicone polymer on a variety of soils, *Environ. Toxicol. Chem.* 14 (1995) 1299.
- [11] R.G. Lehmann, S. Varaprath, C.L. Frye, Degradation of silicone polymers in soil, *Environ. Toxicol. Chem.* 13 (1994) 1061.
- [12] R.G. Lehmann, C.L. Frye, D.A. Tolle, T.C. Zwick, Fate of sludge applied silicones in agricultural soil microcosms, *Water Air Soil Pollut.* 87 (1996) 231.
- [13] S. Varaprath, K.L. Salyers, K. Plotzke, S. M. Nanavati, *Anal. Biochem.* 1998 (accepted for publication).
- [14] Y. Nagai, K. Yamazaki, I. Shiojima, N. Kobori, M. Hayashi, *J. Organomet. Chem.* 9 (1967) 21.
- [15] Joel D. citron, James E. Lyons, Leo Sommer, *J. Org. Chem.* 34 (1969) 638.
- [16] N.N. Sokolov, K.A. Andrianov, S.M. Akimova, *Zhurnal Obshchei Khimii* (English trans.) 26 (1956) 933, pp. 1061–1063.
- [17] K.A. Andrianov, A.I. Chernyavskii, N.N. Makarava, Synthesis of bis [organo-cyclotri(tetra,penta)siloxy]polydimethylsiloxane, *Izv. Akad. SSSR Ser. Khim.* 8 (1979) 1835.
- [18] E.J. Hobbs, M.L. Keplinger, J.C. Calandra, Toxicity of polydimethyl-siloxanes in certain environmental systems, *Environ. Res.* 10 (1975) 397.
- [19] R.J. Watts, S. Kong, C.S. Haling, L. Gearhart, C.L. Frye, B.W. Vigon, Fate and effects of polydimethylsiloxanes on pilot and bench-top activated sludge reactors and anaerobic/aerobic digestors, *Water Res.* 29 (1995) 2405.
- [20] Vladimir Bazant, Vaclav Chvalovsky, Jiri Rathousky, *Organosilicon Compounds*, Academic Press, New York, 1965, p. 42.
- [21] J.A. Cella, J.C. Carpenter, Preparation of  $^{14}\text{C}$ -labeled dimethylsilane-1,1-diol, *J. Label. Compd. Radiopharm.* 34 (5) (1994) 427.