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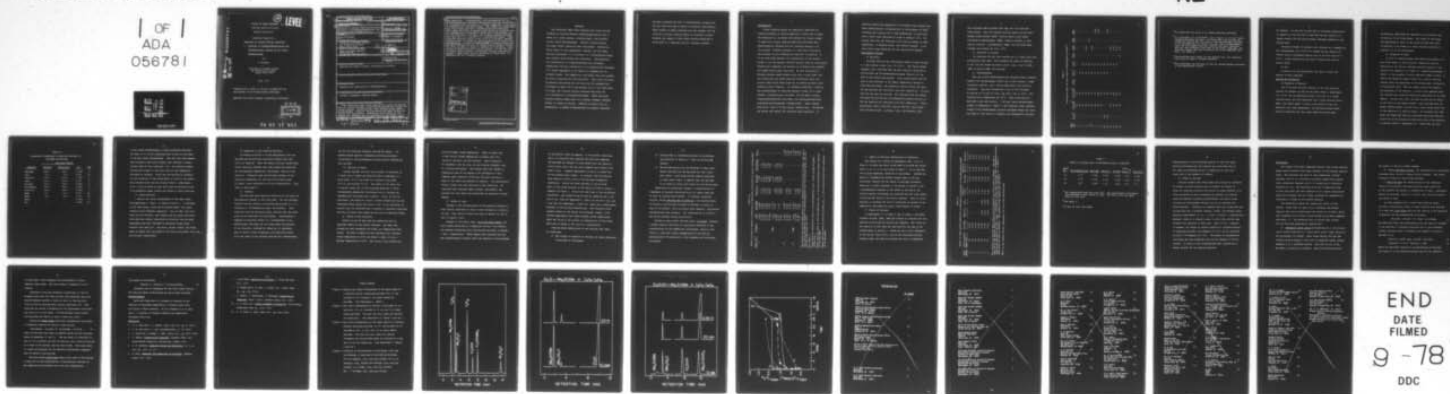
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Technical Report No. 3

CHEMISTRY OF SILANE COUPLING REACTIONS

I. REACTION OF TRIMETHYLMETHOXYSILANE AND
TRIETHYLSILANOL STUDIED BY GAS LIQUID
CHROMATOGRAPHY

by

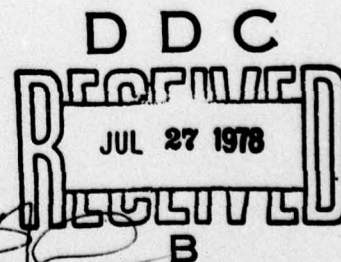
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soon thereafter. Simultaneously, the concentration of trimethylmethoxysilane decreased dramatically and the concentration of triethylsilanol decreased to a degree comparable to the amount of unsymmetrical disiloxane formed. The symmetrical disiloxanes were also present and their concentrations were monitored. After about two hours an apparent equilibrium was attained with the unsymmetrical disiloxane as about 60% of the product, but at very long times, 5-10 days, the reaction mixture contained more than 90% 1,1,1-triethyl-3,3,3-trimethyldisiloxane. These reactions occurred readily either neat or in acetone, benzene, benzene-octane, or octane as solvent. Addition of acetic acid, n-propylamine, or phenyl- β -naphthylamine as possible catalysts may have increased the rate of redistribution slightly but did not alter the type or amount of products significantly. These studies of model reactions give new insight into the function of silane coupling agents in reactions on glass surfaces and suggest a three stage reaction mechanism in which water is a byproduct and not a primary catalyst.

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Abstract

The conditions under which reaction will occur and the products of reaction between trimethylmethoxysilane and a model for a glass surface, triethylsilanol, were studied by gas liquid chromatography. Reaction occurred faster and under milder conditions than anticipated. Immediately after mixing at room temperature, methanol and the unsymmetrical disiloxane, 1,1,1-triethyl-3,3,3-trimethyldisiloxane, were formed; water formed soon thereafter. Simultaneously, the concentration of trimethylmethoxysilane decreased dramatically and the concentration of triethylsilanol decreased to a degree comparable to the amount of unsymmetrical disiloxane formed. The symmetrical disiloxanes were also present and their concentrations were monitored. After about two hours an apparent equilibrium was attained with the unsymmetrical disiloxane as about 60% of the product, but at very long times, 5-10 days, the reaction mixture contained more than 90% 1,1,1-triethyl-3,3,3-trimethyldisiloxane. These reactions occurred readily either neat or in acetone, benzene, benzene-octane, or octane as solvent. Addition of acetic acid, *n*-propylamine, or phenyl- β -naphthylamine as possible catalysts

may have increased the rate of redistribution slightly but did not alter the type or amount or products significantly. These studies of model reactions give new insight into the function of silane coupling agents in reactions on glass surfaces and suggest a three stage reaction mechanism in which water is a byproduct and not a primary catalyst.

Introduction

Silane coupling agents are especially important for promoting bonding of various adhesives to glass and to metal. The formation of a siloxane bond between the silanol groups of glass and a silane coupling agent has previously been demonstrated by infrared and near infrared analysis (1-3). In principal, infrared analysis is a good way of following the progress of this condensation reaction; in practice, it is far from ideal because the concentration of the silanol groups is low and because infrared analysis does not distinguish between pure compounds and mixtures of siloxanes that probably are formed during these reactions. We were interested in forming siloxane bonds between glass and a silane under very mild conditions and needed detailed information about conditions under which these bonds can be formed and about their stability after formation. We therefore undertook a study by gas chromatography of reactions between a model for a glass surface, triethylsilanol (Et_3SiOH), and two model silanes, trimethylmethoxysilane (Me_3SiOMe) and dimethylmethoxysilane terminated poly(butadiene) $[(\text{PB})\text{Me}_2\text{SiOMe}]$. These studies form Parts I and II of this series, respectively. The method has proven very useful for following these reactions. In

previous reports the preparation of siloxanes from silanols and their redistribution (linearization) in the presence of other siloxanes were carried out at high temperature, in polar solvents, and/or were catalyzed by acids or alkalis (1-8). Our studies show that the reactions occur just as readily at room temperature, in nonpolar media, and without catalyst. A revised three stage mechanism for the reaction has emerged.

Experimental Section

a) Materials

Me₃SiOMe from PCR was fractionated under nitrogen through a 5 inch Vigreux column (b.p. 55.5-57°C). Gas liquid chromatography (GLC) indicated that the main fraction consisted of 86% Me₃SiOMe and 14% hexamethyldisiloxane [(Me₃Si)₂O], the same as the undistilled product. Since fractionation did not lead to pure Me₃SiOMe or the sample immediately reacted to form some disiloxane, the apparently stable mixture was used. Its nmr spectrum was consistent with this composition. Et₃SiOH from PCR was used as received. GLC indicated that the sample contained 88% Et₃SiOH and 12% hexaethyldisiloxane [(Et₃Si)₂O]. The nmr spectrum was consistent with this composition. Tetraethylsilane (Et₄Si) from PCR, used as received, was greater than 99% pure by GLC. n-Octane (C₈H₁₈) and benzene (C₆H₆)

were refluxed under nitrogen over CaH_2 for 2 hrs and then fractionated. Only the constant boiling center cut was used. Reagent grade acetone (AcMe), glacial acetic acid (AcOH), and phenyl- β -naphthylamine (PBNA), duPont's Neozone A, were used as received. n-Propylamine (PrNH_2) was distilled under nitrogen just before use (b.p. 48°C).

b) Reactions of Silanes

All reactions for GLC were carried out in 2 dram vials with polyethylene snap caps. With monomers the order of addition to the vial was always Et_3SiOH or Et_4Si , C_8H_{18} , C_6H_6 or AcMe , PrNH_2 or AcOH or PBNA, and Me_3SiOMe .

c) Chromatography

Most gas liquid chromatograms were obtained using a Hewlett Packard 5750 Chromatograph fitted with an SE30 column, a flame ionization detector, and a Perkin-Elmer Model 194B Printing Integrator. The usual program was 4 min at 60°C followed by heating at $60^\circ/\text{min}$ to 160°C , and then 8 min at 160°C . The injection port temperature was 220°C . Some variations are described along with results. A few gas liquid chromatograms, notably in experiment 6, Table I, were obtained using a Hewlett Packard 5710A Chromatograph similarly equipped except that data was taken in real time by a computer and subsequently analyzed

Table I

Quantities Used for Gas Liquid Chromatography Studies^a

Expt. No.	Et ₄ Si ^b	Et ₃ SiOH ^b	Me ₃ SiOMe ^b	SiOMe	C ₈ H ₁₈ ^c	C ₆ H ₆ ^c	AcMe	AcOH	PrNH ₂	PBNA
1	-	96	83	-	-	-	-	-	-	-
2	-	96	83	45	-	-	-	-	-	-
3	-	96	83	35	96	-	-	-	-	-
4	-	96	83	35	96	-	-	0.45	-	-
5	-	96	83	35	96	-	-	-	2.2	-
6 ^d	-	96	83	35	35	-	-	0.45	-	-
7	-	96	83	35	35	-	-	-	-	0.1g
8	-	50	200	35	96	-	-	-	-	0.1g
9	-	96	83	35	35	-	-	-	-	-
10	113	-	83	35	35	-	-	-	-	-
11	113	-	83	35	35	-	-	-	-	0.1g
12	-	96	83	-	35	-	-	0.45	-	-
13	-	96	166	-	35	-	-	0.45	-	-
14	-	96	332	-	35	-	-	0.45	-	-
15	-	96	83	-	-	-	35	0.45	-	-

^aAll quantities are given in μl unless otherwise indicated.

^b96 μl Et_3SiOH = 83 μl Me_3SiOMe = 113 μl Et_3Si = 6.0×10^{-4} moles assuming reactants are pure. As stated above the Et_3SiOH contained 88% Et_3SiOH and 12% $(\text{Et}_3\text{Si})_2\text{O}$ and the Me_3SiOMe consisted of 86% Me_3SiOMe and 14% $(\text{Me}_3\text{Si})_2\text{O}$ by gas liquid chromatography. Since the disiloxanes were also reactive and their densities were not very different from those of the parent compounds, the measured volumes used were calculated as if the compounds were pure. See Table II.

^cConcentrations were chosen so that usually C_8H_{18} but sometimes C_6H_6 could be used as internal standard.

^dThis experiment was followed on both gas chromatographs described in the experimental section.

by computer. In this way we were able to eliminate subjectivity in analysis of the data and to show that the GLC results, although constant for any given program, depended somewhat on the program used.

Molecular weights of monomers were obtained on a Chemalytics MC-2 Chromatogram with 10% DC 410 columns and gas density detectors using a programmed heating rate of $10^{\circ}\text{C}/\text{min}$ from 25 to 250°C . Sulfur hexafluoride and carbon dioxide were used as carrier gases.

d) nmr

A Varian T-60 nmr spectrometer was used to record nmr spectra of neat compounds.

Results and Discussion

a) Formation of Methanol

One of the most striking features of all the reactions carried out between Et_3SiOH and Me_3SiOMe (Table I, Experiments 1-9, 12-15) was the appearance within 10-15 sec of a cloudy solution which very soon separated into a clear solution with a small, more dense phase (a drop) in the bottom of the vial. Retention time, peak enhancement, and molecular weight determination indicated that this lower phase was mainly MeOH .

Deliberately added MeOH was immisible in the mixtures and became part of the lower phase. The volume of this phase was approximately equal to the volume of MeOH that would be expected to be formed in a given reaction according to equation (1) in the conclusions.

b) Formation of water

At first it seemed strange that MeOH should appear in a more dense phase in these mixtures, especially when the densities of the various compounds possibly present in the mixtures are compared as in Table II. Repeating Experiment 2, Table I in the presence of white anhydrous copper sulfate, or adding the anhydrous copper sulfate to a similar reaction mixture after the appearance of the second phase, resulted in a bluish-green drop. When the copper sulfate was added at the beginning of the reaction, a yellow color appeared while the solution was cloudy and before the appearance of the green droplet. Neither neat C_8H_{18} nor neat Et_3SiOH had any effect on the color of the copper sulfate. Neat Me_3SiOMe gave the copper sulfate powder a yellow color, which turned green only on the addition of a trace of water. We concluded that some water was formed and that the relatively more polar MeOH was pulled out of the solution by that water even in the presence of acetone (Table I, Experiment 15). Water does not show

Table II
Properties of Materials in Reaction Mixtures of
Me₃SiOMe and Et₃SiOH

Compound	Molecular Weight		d_4^{20}	Ref
	Observed	Theoretical		
Me ₃ SiOMe	105.5	104.2	0.7560	9
C ₆ H ₆	78.3	78.1	0.879	10
(Me ₃ Si) ₂ O	162.5	162.2	0.7636	9
C ₈ H ₁₈	113.9	114.2	0.703	10
Et ₃ SiOH	139.6	138.3	0.8645	9
Et ₃ SiOSiMe ₃	205.7	204.2	0.8443	9
(Et ₃ Si) ₂ O	246.0	246.2	0.8110	9
MeOH	35	32.0	0.792	10
AcMe	59.3	58.1	0.791	10
Et ₄ Si	-	-	0.7658	9
H ₂ O	-	-	0.9982	10

in gas liquid chromatograms if flame ionization detectors are used, so it is not surprising that we did not see water in our gas liquid chromatograms. Thus the very rapid appearance of MeOH is the first evidence that contrary to expectations based on the literature (1-8), the reaction between Et_3SiOH and silanes is very fast even at room temperature and needs no catalyst. Proof that the Et_3SiOH is necessary for the formation of the second phase is given by the experiments between Et_4Si and the silanes (Table I, Experiments 10,11), since no MeOH or water that could be detected by GLC or by anhydrous copper sulfate was formed in these reactions.

c) Known Materials

A typical gas liquid chromatogram of the upper phase from Experiment 8, Table I is shown in Figure 1. In contrast to the lower phase, which was principally MeOH, this phase contains seven different components. Four of them, two reactants and two solvents, were charged and the peaks associated with them were readily identified by retention time and peak enhancement and were confirmed by molecular weight determination (See Table II). The first, second, fourth, and fifth peaks to appear were thus shown to be those of Me_3SiOMe , C_6H_6 , C_8H_{18} , and Et_3SiOH , respectively.

d) Impurities in the Starting Materials

As stated in Section a of the Experimental Part the Me_3SiOMe and Et_3SiOH each contained slightly more than 10% of an impurity. Their nmr spectra and well-established silane chemistry indicate that these impurities should be the corresponding symmetrical disiloxanes, $(\text{Me}_3\text{Si})_2\text{O}$ and $(\text{Et}_3\text{Si})_2\text{O}$. Retention time and molecular weights of the materials responsible for the third and seventh peaks in Figure 1 were consistent with this interpretation. (See Table II and Figure 1)

e) Products

The only peak that cannot be identified on the basis of the materials charged is the sixth peak. The most probable product from the reaction of Me_3SiOMe and Et_3SiOH is 1,1,1-triethyl-3,3,3-trimethyldisiloxane ($\text{Et}_3\text{SiOSiMe}_3$). Both retention time and molecular weight indicate that the sixth peak can be associated with $\text{Et}_3\text{SiOSiMe}_3$. Significantly a compound of molecular weight 90.2 corresponding to trimethylsilanol (Me_3SiOH) was not found among the products of our reactions, although we looked for it repeatedly. Once or twice a trace of material with molecular weight 86-91 was found in the tracings from the Mc-2 Chromatogram,

but for all practical purposes, Me_3SiOH was absent. Its absence argues against a mechanism involving hydrolysis of Me_3SiOMe to the corresponding silanol before condensation with Et_3SiOH .

f) The Role of Water

Further insight into the role of water in reactions of a silane and a silanol was obtained from an experiment in which water (10 μl) was added to a mixture of Me_3SiOMe (150 μl) and Et_3SiOH (50 μl). The effect of the water was to convert nearly all of both starting materials to their corresponding symmetrical disiloxanes and to increase the unsymmetrical disiloxane only slightly. Since, as will be seen below, the amount of $(\text{Et}_3\text{Si})_2\text{O}$ hardly changed and Et_3SiOH decreased slowly during the first 24 hrs. of our reactions, we believe that our reactions were initiated in anhydrous conditions and that the water that formed did not have an important effect.

g) Effect of GLC Conditions

Tables III and IV show that GLC conditions have an important effect on the results obtained. The same time program was used throughout the study, but temperatures were varied. The data in Table III were obtained with a maximum column temperature of 100°C and those in Table IV with a maximum temperature of 160°C . The $(\text{Et}_3\text{Si})_2\text{O}$ was eluted only

with the higher column temperature. Table IV shows that if the initial column temperature is higher than 70°C, $(\text{Me}_3\text{Si})_2\text{O}$ and C_8H_{18} are not resolved. Since originally we intended to use the C_8H_{18} as the internal standard, this is a serious deficiency. Both Tables show some changes in composition that do not appear to be systematic or vary somewhat under identical conditions even when the data in Table IV was taken and analyzed by computer. The quantitative results clearly are very sensitive to GLC conditions. We concluded that reactions among silanes, disiloxanes, and silanols are very labile and restricted our analysis to gross changes.

h) Effect of Time

Changes in the concentrations of the materials present in each reaction described in Table I were followed as a function of time. Some typical results are given in Tables III and IV and in Figures 3 and 4.

Changes at very short times, 15-30 sec after mixing, are most readily perceived by a comparison of the 10 sec results for mixtures containing Et_4Si and Et_3SiOH and shown in Figures 3 and 4, respectively. These samples were injected into the gas chromatograph as quickly after the addition of the Me_3SiOMe

as the mixture could be sampled. In the mixture containing Et_4Si , no reactions were expected and none were observed. The Me_3SiOMe was charged in large excess over the $(\text{Me}_3\text{Si})_2\text{O}$ (88/14 molar ratio) and the ratio changed only slightly even after 24 hrs. (Compare experiments 10 and 11 in Table III). No new products were formed. In contrast, when Et_3SiOH was used instead of Et_4Si , most of the Me_3SiOMe disappeared immediately. Notice the large decrease in the Me_3SiOMe peak and the large increase in the $(\text{Me}_3\text{Si})_2\text{O}$ peak in Figure 4 compared to Figure 3. Notice also that some of the new product, $\text{Et}_3\text{SiOSiMe}_3$, was formed. As can be seen by comparing the 0 sec. and 10 sec. data for Experiment 9, Table III and the 0 sec. and 2 min data for Experiment 7, Table III, there was a simultaneous decrease in the Et_3SiOH concentration. This decrease corresponded closely to the amount of $\text{Et}_3\text{SiOSiMe}_3$ formed. From similar experiments with higher maximum column temperatures where the $(\text{Et}_3\text{Si})_2\text{O}$ was eluted, we learned that at this stage there was no change in the $(\text{Et}_3\text{Si})_2\text{O}$ concentration.

From the above observations we can conclude that under our conditions

- a) The silanol is required to catalyze the rapid conversion of Me_3SiOMe to disiloxanes.

- b) The Me_3SiOMe is converted partially to $\text{Et}_3\text{SiOSiMe}_3$ and partially to $(\text{Me}_3\text{Si})_2\text{O}$. Very little Me_3SiOMe remains.
- c) The Et_3SiOH reacts with the Me_3SiOMe or some intermediate derived from the Me_3SiOMe but very little with itself. Since much Et_3SiOH remains unreacted at these short times, it appears that the Me_3SiOMe is as likely to react with itself as with the Et_3SiOH .

There were no significant changes in concentrations of components of mixtures containing Et_4Si at longer times and we will not discuss them further. In mixtures containing Et_3SiOH , during the next two to three hrs, the concentrations of $(\text{Me}_3\text{Si})_2\text{O}$ and Et_3SiOH continued to decrease in favor of that of $\text{Et}_3\text{SiOSiMe}_3$, which increased until apparent equilibrium concentrations were achieved. The concentration of $(\text{Et}_3\text{Si})_2\text{O}$ was fairly constant during this period.

Studies at much longer reaction times, 1-10 days, revealed a slower reaction resulting in significant decreases in the concentrations of the symmetrical disiloxanes, $(\text{Me}_3\text{Si})_2\text{O}$ and $(\text{Et}_3\text{Si})_2\text{O}$, plus the virtual disappearance of Et_3SiOH and yielding about 90% conversion to the unsymmetrical disiloxane, $\text{Et}_3\text{SiOSiMe}_3$.

Table III

Effect of Time on Amounts of Materials in Reactions of Et₃SiOH (or Et₄Si) and Me₃SiOMe^a

Expt. No. ^b	Catalyst	Time	Me ₃ SiOMe	(Me ₃ Si) ₂ O	Et ₃ SiOH	Et ₃ SiOSiMe ₃	Et ₄ Si
9	-	0 sec	0.660 ^c	-	1.70 ^d	-	-
		10 sec	0.137	0.575	1.37	1.16	-
		30 min	0.052	0.322	0.595	1.80	-
		2.6 hr	0.123	0.227	0.225	1.93	-
		24 hr	0.086	0.358	0.245	1.78	-
		10 days	0.201	Trace	Trace	2.89	-
7	PBNA	0 sec	0.660 ^c	-	1.70 ^d	-	-
		2 min	0.167	0.506	1.00	1.15	-
		28 min	-	0.552	0.668	1.32	-
		24 hr	0.092	0.288	0.282	1.76	-
		10 day	-	Trace	0.078	2.83	-
10	-	0 sec	0.660 ^c	-	-	-	1.61 ^e
		10 sec	0.667	0.079	-	-	1.62
		67 min	0.617	0.248	-	-	1.62
		24 hr	0.502	0.203	-	-	1.44
11	PBNA	0 sec	0.660 ^c	-	-	-	1.61 ^e
		3.5 min	0.519	0.027	-	-	1.54
		20 min	0.617	0.248	-	-	1.62
		24 hr	0.468	0.102	-	-	1.47

^a All amounts are for the upper phase and are expressed as area ratios to octane. The GLC's were run on the Hewlett Packard 5750 Chromatograph with the usual program except that the maximum temperature was 100°C.

^b See Table I.

^c Taken from the calibration curve of area Me₃SiOMe/area C₈H₁₈ versus volume Me₃SiOMe/volume C₈H₁₈.

^d Taken from the ratio of area Et₃SiOH/area C₈H₁₈ in the reaction mixture before addition of the Me₃SiOMe.

^e Taken from the ratio of area Et₄Si/area C₈H₁₈ in the reaction mixture before addition of the Me₃SiOMe.

i) Effect of Relative Concentration of Reactants

The results of a series of experiments (Nos. 12-14 in Table I) in which the ratio of Me_3SiOMe to Et_3SiOH was varied from 1:1 to 2:1 to 4:1 are given in Table V. In no case was the Et_3SiOH completely converted to $\text{Et}_3\text{SiOSiMe}_3$. Instead the amount of unsymmetrical product formed after 24 hrs was relatively constant and the amount of Me_3SiOMe increased. There was a notable decrease in the amount of $(\text{Et}_3\text{Si})_2\text{O}$ and a corresponding increase in the amount of Et_4SiOH as the relative amount of Me_3SiOMe was increased but the total amount of Et_3SiOH and $(\text{Et}_3\text{Si})_2\text{O}$ was fairly constant. Thus it is not possible to increase the rate of conversion of silanol to unsymmetrical disiloxane by using a large excess of silane.

j) Effect of Catalyst

In experiments 3-7 of Table I and in Figure 4 the effectiveness of AcOH , PrNH_2 , PBNA and nothing as catalysts for the coupling of Me_3SiOMe and Et_3SiOH was compared. The course of the reaction in each case was qualitatively the same as described above in section c. There was very little difference in the initial rate of formation of the disiloxane mixture. Possibly PrNH_2 and AcOH did increase the rate of subsequent

Table IV

Effect of Time and GLC Conditions on Materials in Reactions of Et ₃ SiOH and Me ₃ SiOMe ^a									
Time (Days)	Initial Column Temp (°C) ^b	Me ₃ SiOMe	(Me ₃ Si) ₂ O	C ₈ H ₁₈	(Me ₃ Si) ₂ O + C ₈ H ₁₈	Et ₃ SiOH	Me ₃ Si Et ₃ Si	O	(Et ₃ Si) ₂ O
1	80	0.072	-	-	0.83	0.22	3.61		0.49
2	80	0.059	-	-	0.79	0.07	3.02		0.58
5	80	0.050	-	-	0.69	0.05	2.30		0.72
5	80	0.049	-	-	0.79	0.05	1.99		0.71
5	70	0.050	0.247	0.447	0.69	0.05	2.30		0.72
5	60	0.052	0.313	0.523	0.83	0.15	2.81		0.85
5	60	0.053	0.253	0.603	0.86	0.16	2.88		0.85

^aAll amounts are for the upper phase and are expressed as area ratios to benzene. The GLC's were run on the Hewlett Packard 5710A Chromatograph. Under some conditions this chromatograph did not resolve the (Me₃Si)₂O and C₈H₁₈ peaks. All data is derived from experiment No. 6, Table I where HOAc was used as catalyst. The maximum column temperature was 160°C.

^b80°C is the normal initial temperature for the 5710A Chromatograph.

Table V

Effect of Varying Ratio of Me₃SiMe/Et₃SiOH on Products^a

Expt ^b No	Me ₃ SiOMe/Et ₃ SiOH	Me ₃ SiOMe	(Me ₃ Si) ₂ O	Et ₃ SiOH	$\begin{array}{c} \text{Et}_3\text{Si} \\ \diagup \quad \diagdown \\ \text{Me}_3\text{Si} \quad \text{O} \end{array}$	(Et ₃ Si) ₂ O
14	1:1 ^c	0.012	0.223	0.061	1.46	0.560
15	2:1 ^c	0.333	0.776	0.420	1.68	0.199
16	4:1 ^c	0.836	1.11	0.614	1.13	0.0

^a The standard GLC conditions were used. The concentration of products are expressed as area ratios to C₆H₆. The data is for the upper phase in each case.

^b See Table I.

^c In C₆H₆. No C₈H₁₈ was added.

redistribution of the disiloxane mixture to form the unsymmetrical disiloxane but the reaction was relatively slow in all cases and proceeded nearly to completion at very long times even in the absence of catalyst.

k) Effect of Solvent

Previous workers have used either neat silanes or solutions of silanes in polar solvents such as ethanol or acetone to carry out coupling reactions with silica or glass surfaces (1-8). Since ultimately we were interested in carrying out coupling reactions between silanated poly(butadiene) and glass, polar solvents are unacceptable because they do not dissolve the poly(butadiene). Therefore we compared reactions of Me_3SiOMe and Et_3SiOH neat and in acetone, benzene, octane, and benzene-octane mixtures (experiments 15, 12, 2, 6 and 4 in Table I, respectively). Methanol formed as a separate phase in every case and the same products were observed in each case. After 24 hrs., compared to benzene, the change to acetone resulted in increased amounts of unreacted Me_3SiOMe (12% compared to 0.5%) and of unreacted Et_3SiOH (3.0% compared to 2.0%). The amount of unsymmetrical disiloxane was also decreased from 63% for benzene to 47% for acetone. At least at the concentrations used, benzene was a better solvent for the coupling reaction.

Conclusions

Our studies with model compounds indicate that silane coupling agents should interact with glass surfaces to form primary chemical bonds. The reactions can occur at room temperature, without catalyst, neat or in a variety of solvents ranging from acetone with a dielectric constant of 20.7 to octane with a dielectric constant of 1.95. The reactions do not go to completion even at very long times and there appears to be a dynamic equilibrium among the siloxanes that are formed, although the unsymmetrical disiloxane is formed in the largest quantity.

The mechanism by which the interaction occurs is less certain. Water does not seem to be a necessary and primary catalyst that acts by hydrolyzing the silane to a silanol, which then condenses with existing silanol groups as has been suggested previously (1). Any mechanism that is written must account for the following experimental observations:

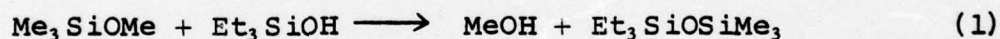
a) Immediately after mixing $\text{Me}_3\text{SiOMe}/(\text{Me}_3\text{Si})_2\text{O}$ (86/14 molar ratio) and $\text{Et}_3\text{SiOH}/(\text{Et}_3\text{Si})_2\text{O}$ (88/12 molar ratio), MeOH , $(\text{Me}_3\text{Si})_2\text{O}$, and $\text{Et}_3\text{SiOSiMe}_3$ are formed. Water forms rapidly also but the slightly delayed change in the color of anhydrous copper sulfate suggests it is a secondary product. Most but not all of the Me_3SiOMe is converted to products. Much Et_3SiOH persists and

the amount of $(\text{Et}_3\text{Si})_2\text{O}$ hardly changes.

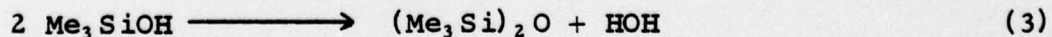
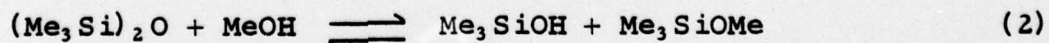
b) During the next 2-24 hrs. the concentration of $\text{Et}_3\text{SiOSiMe}_3$ increases while $(\text{Et}_3\text{Si})_2\text{O}$ remains fairly constant. The concentrations of $(\text{Me}_3\text{Si})_2\text{O}$ and Et_3SiOH decrease.

c) From 1-10 days the concentrations of the remaining $(\text{Me}_3\text{Si})_2\text{O}$ and $(\text{Et}_3\text{Si})_2\text{O}$ decrease gradually until about 90% of the possible $\text{Et}_3\text{SiOSiMe}_3$ is formed after 10 days. Detectable amounts of Me_3SiOMe , $(\text{Me}_3\text{Si})_2\text{O}$, Et_3SiOH and $(\text{Et}_3\text{Si})_2\text{O}$ persist even after 10 days.

Our data suggests that a three stage reaction occurs. Et_3SiOH is sufficiently acidic to react directly with Me_3SiOMe in a very fast first stage reaction that results in the formation of methanol and the unsymmetrical disiloxane:



The MeOH that forms then equilibrates with the $(\text{Me}_3\text{Si})_2\text{O}$ present in the Me_3SiOMe to regenerate Me_3SiOMe and to form trimethylsilanol, Me_3SiOH , which is unstable with respect to $(\text{Me}_3\text{Si})_2\text{O}$ and HOH (4,13):

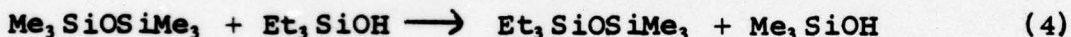


These two reactions account for the persistence of Me_3SiOMe and $(\text{Me}_3\text{Si})_2\text{O}$ in our reaction mixtures and for the formation

of some water, which combines with the methanol to form a separate lower phase. The first stage is complete in 15-30 seconds.

Reactions of Et_3SiOH analogous to equations (2) and (3) probably also occur but they are much less important than with Me_3SiOH because Et_3SiOH is known to react in this way only 1/600 as fast as Me_3SiOH under similar conditions (11). The reactions do provide a mechanism for the persistence of Et_3SiOH and $(\text{Et}_3\text{Si})_2\text{O}$ at long times. Et_3SiOH probably reacts faster with Me_3SiOMe and $(\text{Me}_3\text{Si})_2\text{O}$ than it does with itself.

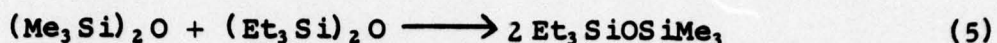
During the second stage additional unsymmetrical disiloxane is formed by reaction of $(\text{Me}_3\text{Si})_2\text{O}$ with Et_3SiOH



Again the Me_3SiOH that forms is removed rapidly by the reactions shown in equations (2) and (3). The net result of reactions (3) and (4) is to convert one mole of $(\text{Me}_3\text{Si})_2\text{O}$ and 2 moles of Et_3SiOH to 2 moles of $\text{Et}_3\text{SiOSiMe}_3$ and one mole of HOH . This stage takes 2-3 hours and accounts for the observed simultaneous disappearance of $(\text{Me}_3\text{Si})_2\text{O}$ and Et_3SiOH .

The much slower third stage begins after most of the Et_3SiOH is gone and is the redistribution (linearization) reaction of the symmetrical disiloxanes that gives the unsymmetrical

disiloxane as the product



Catalysts are not necessary for the first stage reaction but they may speed up the second and third stage reactions.

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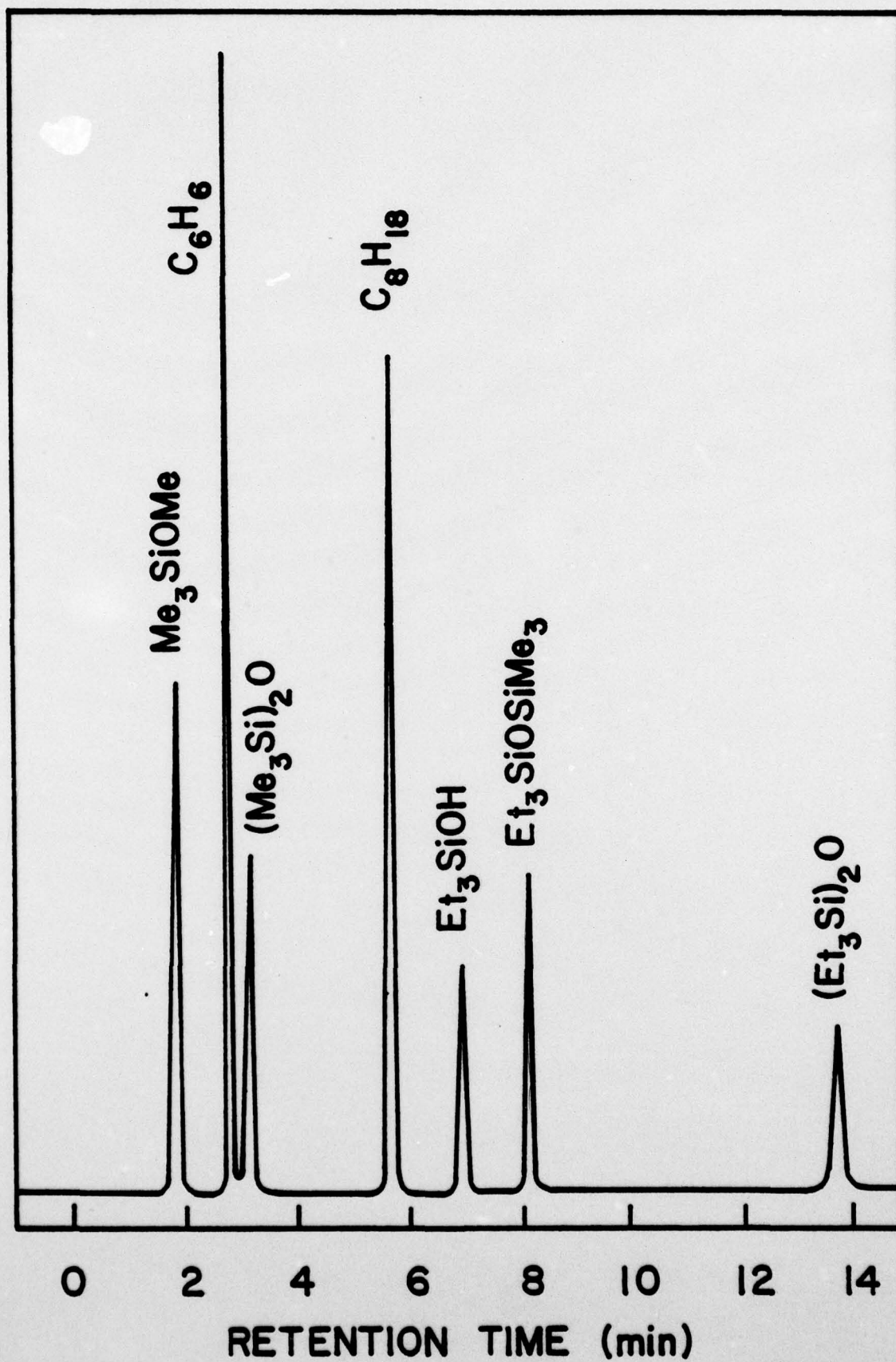
Figure Legends

Figure 1--Typical gas liquid chromatogram of the upper phase of a reaction mixture containing Me_3SiOMe (200 μl) and Et_3SiOH (50 μl) recorded 5 min after adding the Me_3SiOMe . (See Experiment 8, Table I.)

Figure 2--Gas liquid chromatogram of mixture of Me_3SiOMe (83 μl) and Et_4Si (111 μl) recorded at 10 sec and 24 hr after adding Me_3SiOMe . The C_6H_6 and C_8H_{18} peaks are omitted for simplicity. (See Experiment 10, Tables I and III.)

Figure 3--Gas liquid chromatogram of the upper phase of a reaction mixture containing Me_3SiOMe (83 μl) and Et_3SiOH (96 μl) recorded 10 sec, 30 min, and 2.58 hr after adding Me_3SiOMe . The C_6H_6 and C_8H_{18} peaks are omitted throughout and the Me_3SiOMe peaks are omitted at 30 min and 2.58 hr for simplicity. (See Experiment 9, Tables I and III.)

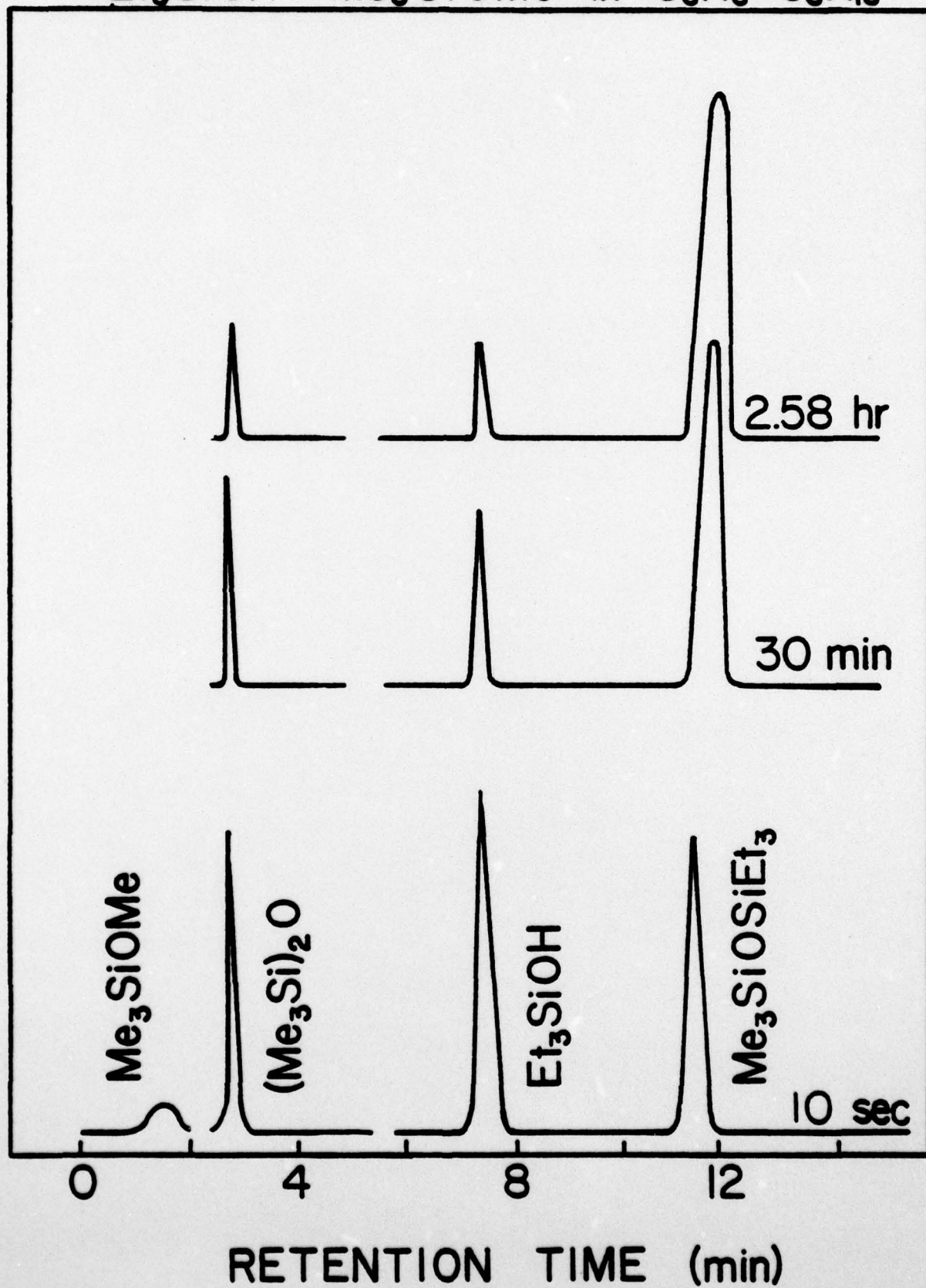
Figure 4--Variation of concentration of $\text{Et}_3\text{SiOSiMe}_3$ with time and catalyst in reactions of Et_3SiOH and Me_3SiOMe .
O—O no catalyst, C_8H_{18} and C_6H_6 solvent; x---x, no catalyst, C_8H_{18} solvent; $\square$ — $\square$ AcOH , C_8H_{18} and C_6H_6 solvent; Δ --- Δ PrNH_2 , C_8H_{18} and C_6H_6 solvent;
 $\bullet$ — $\bullet$ PBNA , C_8H_{18} and C_6H_6 solvent.

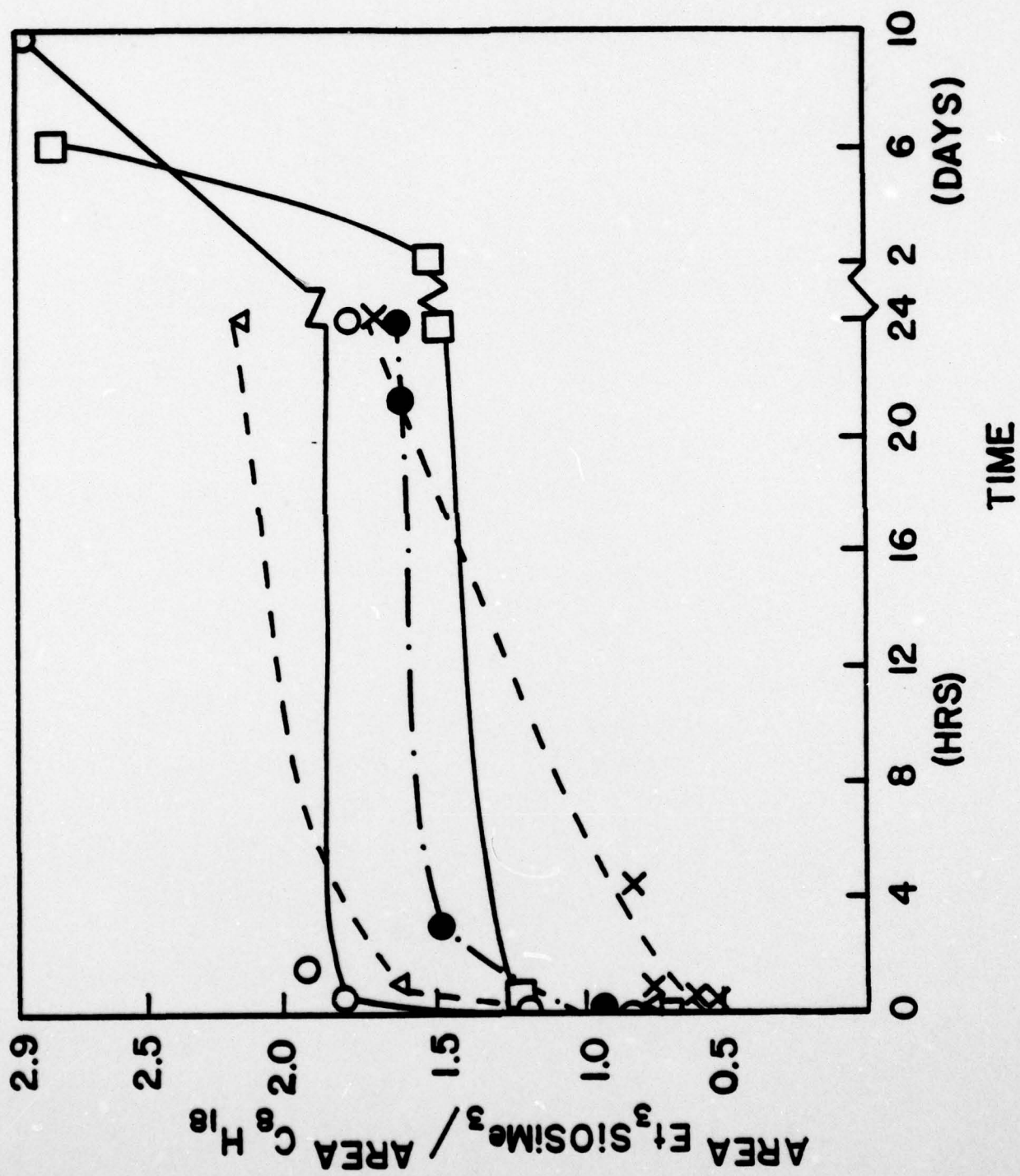


$\text{Et}_4\text{Si} + \text{Me}_3\text{SiOMe}$ in $\text{C}_6\text{H}_6\text{-C}_8\text{H}_{18}$



$\text{Et}_3\text{SiOH} + \text{Me}_3\text{SiOMe}$ in $\text{C}_6\text{H}_6 - \text{C}_8\text{H}_{18}$





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