To the Graduate Council:

I am submitting herewith a dissertation written by George Hondrogiannis, entitled "I. The Cycloaddition Reactions of Methyl and (-)-Menthyl Acrylates with Cyclopentadiene on γ-Alumina; II. The Hydroboration of Alkenylcarboranes." I have examined the final copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Chemistry.

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Associate Vice Chancellor
and Dean of The Graduate School

I. THE CYCLOADDITION REACTIONS OF METHYL AND (-)-MENTHYL ACRYLATES WITH CYCLOPENTADIENE ON γ-ALUMINA; II. THE HYDROBORATION OF ALKENYLCARBORANES

A Dissertation

Presented for the

Doctor of Philosophy Degree

The University of Tennessee, Knoxville

George Hondrogiannis

May, 1995

This work is dedicated to my wife, Ellen Kurt Hondrogiannis.

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The author wishes to express his gratitude to Dr. George W. Kabalka, for his patience, guidance, encouragement, and assistance in completing this work. The author also wishes to thank Dr. Richard M. Pagni for his valuable assistance, suggestions and frienship. Appreciation is expressed to the Department of Chemistry, University of Tennessee for a Graduate Teaching Assistanship, and to the late Dr. Gleb Mamantov for recruting me.

ABSTRACT

The hydroboration of representative alkenyl-*ortho*-carboranes with borane-tetrahydrofuran (BH_3·THF), 9-borabicyclo[3.3.1]nonane (9-BBN), and dicyclohexylborane (Chx_2BH) was investigated systematically to establish the rates, stoichiometry and directive effects in the hydroboration. The cage exerts a profound effect in the rate and the regioselectivity particularly for the vinyl derivatives of carborane. The directive effect observed for vinylcarborane and propenylcarborane with borane results in an considerable amount of α-organoboranes, as compared to β. The directive effect observed for isopropenylcarborane with borane results in the exclusive formation of the β-organoborane. Likewise the directive effect observed for allylcarborane and hexylallylcarborane is significant and favors the internal carbon. With increasing distance from the cage the ability of the cage to direct boron in the internal carbon decreases. Hydroboration with 9-BBN and Chx_2BH results in a remarkable regioselectivity for the terminal position in all cases.

The Diels-Alder reaction of cyclopentadiene (CP) with methyl (MA) and (-)-menthyl (MNA) acrylates on alunima of varying catalytic activity has been studied.

The diastereophase-selectivity of the reaction of CP with MNA, and particularly the diasteroselectivity of the reaction of CP with MA, are markedly dependent on the activity of the alumina. The results can be explained by two factors: (1) the nature and the number of the active sites on the surface, and (2)

the facile retroversion of the cycloadduts on the more activated alumina. The reaction of CP with MA has been used to measure the polarity of the surface being express by the Ω value. The Ω value of the surface of unactivated alumina was shown to be 0.740 ± 0.024 which suggests that the surface has a polarity comparable to ethanol and acetic acid.

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PART I. THE HYDROBORATION OF ALKENYLCARBORANES

CHAPTER I

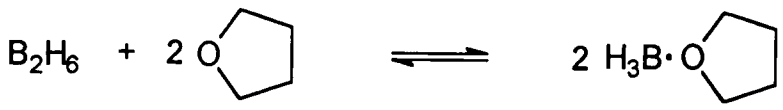
Introduction

The subject of Part I of this dissertation is the study of the hydroboration reaction of 1-alkenyl and 1-alkenyl-2-alkyl-*o*-carboranes with hydroborating agents of different steric requirements. In order to better understand the nature of the subject, a general background of the hydroboration reaction is presented first. Since the olefins to be hydroborated contain *o*-carboranes, a general overview of the properties and reactivity of this unusual chemical moiety is also presented. Besides *o*-carborane, the isomeric *m*- and *p*-carboranes are also known. In order to better evaluate the physical properties of the *o*-carborane, a comparison with those of the *m*-isomer is briefly presented in the introduction. According to IUPAC nomenclature, the names of the isomers in the order mentioned are 1,2-, 1,7-, and 1,12-dicarba-*closo*-dodecaboranes.

1.1 *Hydroboration Reaction*

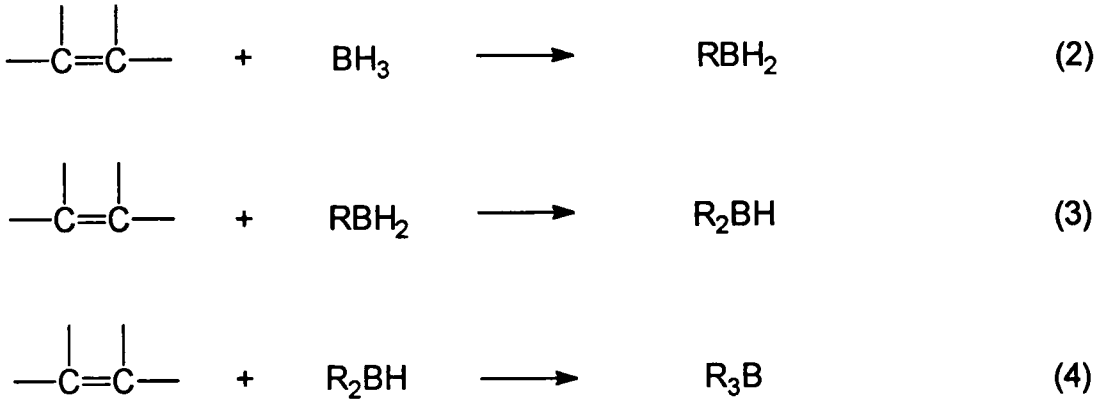
The hydroboration reaction involves the addition of boron and hydrogen to carbon-carbon double and triple bonds (1-5). The reaction, in solution at 25 °C or at 0 °C, proceeds rapidly in the presence of a donor solvent, in contrast to the sluggish gas phase reaction (6-10). The catalytic effect of donor solvents such as ethers and sulfides on the hydroboration reaction is due to their ability to dissociate diborane from a hydrogen-bridged dimeric species into an approximately tetrahedral borane-ether complex, which is the reactive species in

the hydroboration reaction (1-3, 11,12) (eq 1).



(1)

The addition of borane to alkenes involves three distinct stages in which one, two, or three carbon-boron bonds may be formed (1-3) (eq 2-4).



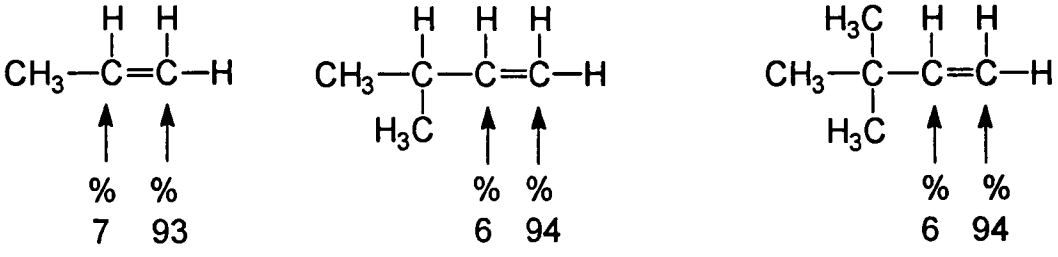
Which intermediate forms depends mainly on the structure of the alkene and to some extent on the reaction conditions. Thus terminal alkenes and some unhindered internal alkenes give trialkylboranes regardless of the ratio of reagents used (2-6, 13-15). Trisubstituted and more hindered internal disubstituted alkenes form dialkylboranes very quickly with further reaction being slow (2-6,13-15). Finally, the reaction can proceed such that only a single carbon-boron bond is formed, provided that a sufficiently bulky alkene is used (2-6, 13-15)

Many dialkyl- and monoalkylboranes find utility in the syntheses of mixed trialkylborane intermediates, which in turn undergo a variety of useful synthetic

transformations (1-3, 16). Dialkylboranes are also used when control of regioselectivity and/or reactivity is desired (17-20). Carbon-carbon double and triple bonds (21-24) show much higher reactivity toward boron hydrides than many functional groups which enhances the synthetic utility of the method (25-29).

The importance of steric effects in the hydroboration reaction is demonstrated by their influence on the stoichiometry and regioselectivity of the reaction. The stoichiometry of the reaction, in terms of the hydrides used per borane equivalent, depends upon the steric bulk of the alkyl groups attached not only to the carbon atoms of the double bond, but also those on the boron atom of the hydroborating agent (13). Steric effects influence the regioselectivity of addition by directing boron to the less substituted carbon of the double bond, and this preference can be increased by the employment of bulky substituted boranes (1-3). Evidence, however, indicates that steric effects are not the only factor controlling the regioselectivity of the reaction. Thus, as one increases the size of the alkyl group bonded to ethylene, very little change in the placement of boron is noted (30) (Chart 1).

Chart 1

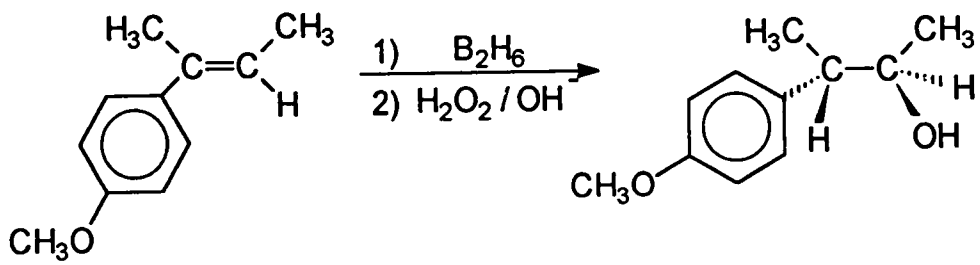


Strong evidence in favor of electronic effects has been obtained using functionalized alkenes that influence the direction of addition (1-3, 30). These effects were explained in terms of stabilization of small partial charges at the carbon atoms of the double bond in the transition state by electron shifts in the reacting alkene.

1.1.1 *Stereochemistry and Mechanism*

The hydroboration of alkenes involves the *syn* addition of the boron-hydride moiety to the double bond from the less hindered side. This conclusion was based on stereochemical studies of hydroboration-oxidation and hydroboration-protonolysis reactions which assumed retention of configuration during the deboronation step (14).

Winstein was among the first to show that hydroboration-oxidation of *cis*- and *trans*-2-*p*-anisyl-2-butene gave *threo*- and *erythro*-3-*p*-anisyl-2-butanols, respectively, by a *syn*-hydration of the double bond (31) (eq 5,6).



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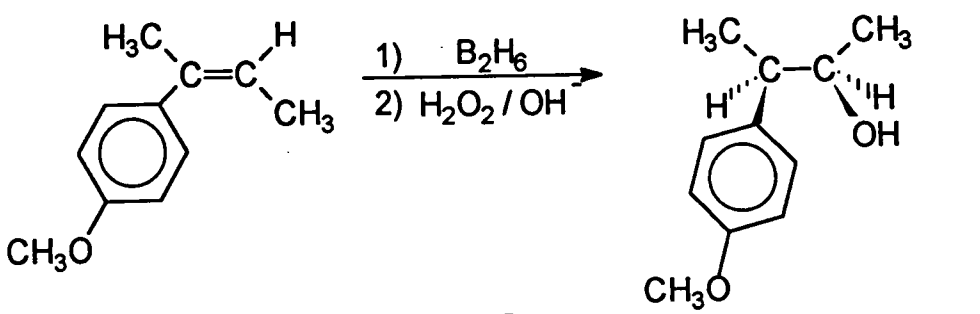
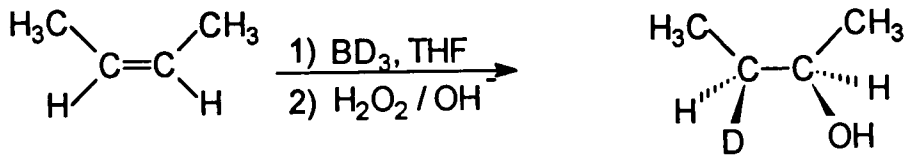


(6)

Similar conclusions were reached by Brown and Zweifel who obtained *trans*-2-methylcyclopentanol and *trans*-2-methylcyclohexanol by the hydroboration-oxidation of 1-methylcyclopentene and 1-methylcyclohexene, respectively (32). Further proof of the stereospecific *syn*-hydration of simple alkenes was provided by Kabalka and Bowman (33) who studied the deuteroboration of the conformationally biased *cis*-2-butene and *trans*-2-butene followed by oxidation. The former afforded *erythro*-2-butanol-3-d (eq 7) and the latter *threo*-2-butanol-3-d (eq 8).



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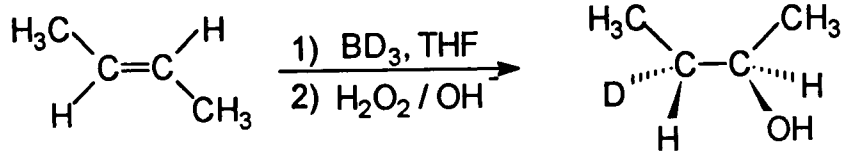


(8)

Evidence confirming the stereochemistry of the reaction was obtained by Kabalka and co-workers who based their conclusions on NMR studies of the organoboranes obtained from isomeric deuterated 1-hexenes (34). Additional evidence that the reaction proceeds from the sterically less hindered side of the double bond was provided by a study of hydroboration-oxidation of norbornene (35) which gave nearly pure *exo*-norborneol. Similarly, α-pinene (14), camphene (36), longifolene (37), cholesterol (38), and many other compounds have been

shown to react with borane from the less hindered side. The stereospecificity of the reaction can be further improved by the employment of more sterically demanding borane derivatives (39,40). Based on the regioselectivity, the stereospecific *syn* addition of the B-H moiety, and the lack of rearrangement, Brown proposed that hydroboration takes place via a concerted four-center transition state (1,30) (Figure 1).

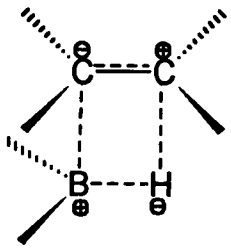


Figure 1. Transition state of the reaction of borane with alkenes.

Although this model readily explains both steric and electronic effects exerted by the substituents, it is not in agreement with some experimental results. Thus it fails to predict the configuration of 1-deuterio-1-butanol which is formed by the asymmetric hydroboration of *cis*-1-deuteriobutene with diisopinocamphenylborane (40). This led to other mechanisms being proposed (41-48). The most reasonable of these postulates is that the hydroboration reaction proceeds as a two-stage process involving the formation of a symmetry-allowed, three-center, two-electron π-complex which, in a subsequent rate determining process, is converted to the final product via a four-center transition state (48).

1.1.2 *Kinetics*

Kinetic studies of the hydroboration reaction with borane are difficult because the overall process involves three sequential reactions (eq. 2-4), five monomer-dimer equilibria (eq. 9-13) and three redistribution equilibria (eq. 14-16).

Monomer-dimer equilibria:

$$RBH_2 + BH_3 \rightleftharpoons RHBH_2BH_2 \quad (9)$$

$$R_2BH + BH_3 \rightleftharpoons R_2BH_2BH_2 \quad (10)$$

$$2RBH_2 \rightleftharpoons RHBH_2BHR \quad (11)$$

$$2R_2BH \rightleftharpoons R_2BH_2BR_2 \quad (12)$$

$$RBH_2 + R_2BH \rightleftharpoons RHBH_2BR_2 \quad (13)$$

Redistribution equilibria:

$$BH_3 + R_3B \rightleftharpoons R_2BH + RBH_2 \quad (14)$$

$$2RBH_2 \rightleftharpoons R_2BH + BH_3 \quad (15)$$

$$2R_2BH \rightleftharpoons RBH_2 + R_3B \quad (16)$$

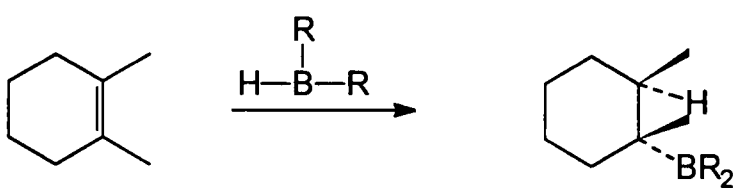
Furthermore, the addition of boron to simple alkenes is too fast to be measured by conventional methods (4). Relative reactivities of various alkenes with borane have thus been measured by competitive reactions (4).

Rate values for addition of the second alkene (eq. 2), relative to the first (eq. 3), have been estimated for a number of alkenes; k_2 was found to be always larger than k_1 by factors ranging from 14 to 43 (49). Furthermore, it was found that rate constants for the disproportionation of RBH_2 (eq 15) were, about one-hundredth the

value of k_2. Consequently, the dominant formation of dialkylborane in the hydroboration with borane occurs via consecutive addition reactions and not by an addition-redistribution pathway. Similarly, the rate of formation of R_3B from R_2BH and alkene (eq 4) was found to be much faster than the rate of formation of R_3B by disproportionation of R_2BH (eq 16) (48).

The effect of alkyl substitution on boron on the monomer-dimer equilibrium constants (eq. 8-13) has been explained in terms of a balance between the steric effects in the alkylborane·THF complexes and those in the hydrogen bridged dimers. Thus, as the number and size of the alkyl groups on boron increases, the stability of the alkylborane·THF complex decreases, which shifts the equilibrium toward the dimeric species. The dimeric species, however, are not very reactive hydroboration reagents, and thus it is assumed that the monomeric form of the alkylboranes reacts with alkenes. The increase in reactivity of the borane derivatives relative to borane is attributed to a decrease in the stability of their THF·complexes due to steric effects (11).

Analysis of the products of the reaction of borane with 1,2-dimethyl cyclohexene indicates that the products are those of kinetic control (50) (eq 17).



(17)

These results support an early transition state which is close in energy and structure to the ground state. Tritium isotope effects $^1H/^3H$ indicate a more highly developed transition state with monosubstituted alkenes (k_H/k_T = 10-11.5) as opposed to disubstituted alkenes (k_H/k_T = 8.7-9.1), trisubstituted (k_H/k_T = 4.2), and tetrasubstituted tetramethylethylene (k_H/k_T = 3.4) (49).

The reaction of styrene with borane was found to be pseudo-first order in styrene and first order in borane (51). In a similar study with chloroborane in tetrahydrofuran, first order dependence in both styrene and chloroborane was discovered (12). Second order kinetics were also found in the reaction of borane in tetrahydrofuran with tetramethylethylene, first order in each, with a second order rate constant of 1.482 $l \cdot mol^{-1}s^{-1}$ at 25°C; $\Delta H^{\ddagger}$ = 38.5 ± 1.7 kJ $mole^{-1}$ and $\Delta S^{\ddagger}$ = -113 ± 4 $kJ^{-1} \cdot mol^{-1}$ (11, 47). These activation parameters led researchers to exclude free borane as the hydroboration agent and suggest a transition state in which the tetrahydrofuran must be only partly loosened from borane (11).

The rates of hydroboration of substituted styrenes with borane and monochloroborane have been correlated using the Hammett equation. In one study (12), carried out with borane in diglyme, it was shown that a plot of log (k_b/k_a) against σ^+ was linear with a slope of -0.7. In another study, in a large excess of borane-THF, Klein and co-workers (51) found that the rate of hydroboration of substituted styrenes was not governed by a single Hammett correlation. In the latter study, the log k/k_o vs. σ for addition of boron at the α-position of the *meta*- and *para*-substituted styrenes, and at the β-position of the *meta*-substituted styrenes, produced

linear correlations with ρ values of .05, 1.2 and -.05 respectively. Finally, with monochloroborane in THF, the distribution of boron on the primary and secondary carbons of styrenes was correlated with the σ scale of the substituents with ρ = -.65 (12). The low ρ values obtained in all these studies indicate a small charge development in both carbon atoms of the double bond in the transition state of the rate determining step of the reaction. Such results are in agreement with a four-center transition state.

In an attempt to avoid the complexities associated with the borane reactions, the kinetics of alkene hydroborations were carried out using dialkylboranes. In contrast to borane, these compounds exist as dimers in ether solvents (49,52,53). For simple reactive olefins such as cyclopentene, hydroboration with bis(3-methyl-2-butyl)borane showed second order kinetics (53); they were first order in the alkene and first order in the dimer. Kinetic studies using 9-BBN generated very interesting results (54,55). With more reactive alkenes (i.e., 1-hexene, 2-methyl-1-pentene, and cyclopentene), the reaction is first order in the dimer and zero order in alkene. On the other hand, with less reactive alkenes (i.e., cyclohexene, 2,3-dimethyl-2-butene and 1-methylcyclohexene) the reaction exhibits three-halves-order kinetics, first order in alkene and one-half order in dimer. Thus it appears that, with more reactive alkenes, the dissociation of the dimer is slower than the subsequent reaction between the monomer and the alkene which leads to first-order kinetics. With less reactive alkenes, the addition of the monomer to the alkenes becomes the rate determining step which leads to a three-halves-order kinetics. Finally, in the hydroboration of

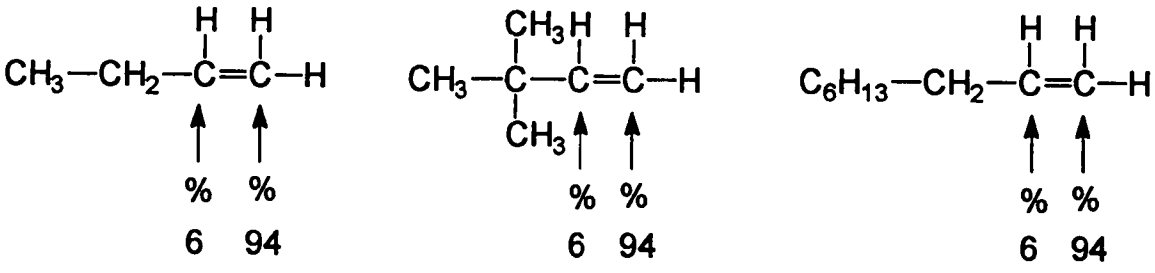
substituted styrenes with borabicyclo[3.3.1]nonane (9-BBN), a linear plot of log (k/k_o) against σ^+ with ρ = -.49 was obtained, indicating a small build up of positive charge at the α-carbon of the styrene (56).

1.1.3 *Directive Effects in the Hydroboration non-Functionalized Alkenes*

Study of the regioselectivity of the addition of boron to alkenes and alkynes is generally carried out by oxidizing the hydroboration products with alkaline hydrogen peroxide or sodium perborate in aqueous tetrahydrofuran (40,57). Since the hydroxy group replaces the boron with retention of configuration, analysis of the alcohols serves to locate the precise position of the boron atom in the original organoboranes (40).

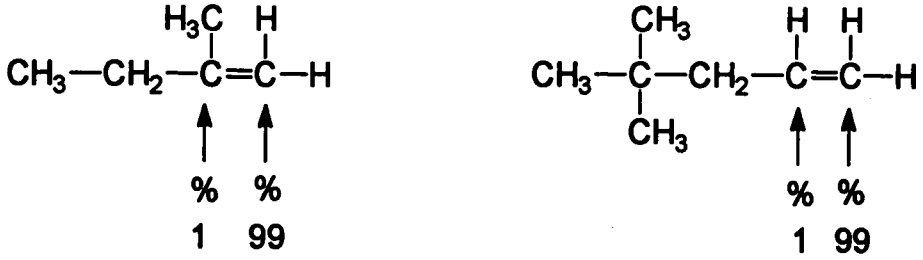
The hydrobortion-oxidation of terminal alkenes is a procedure which generates anti-Markovnikoff alcohols, even though, if one considers the polarization of the B^+–H^- bond, the addition of boron hydrides to alkenes conforms to Markovnnikoff's rule (1-3). Monosubstituted terminal alkenes $RCH=CH_2$ react with borane to place 94% of the boron at the terminal carbon. Branching of the carbon chain in the α-position of the alkene does not increase the regioselectivity of the addition (1-3,40) (Chart 2).

Chart 2.



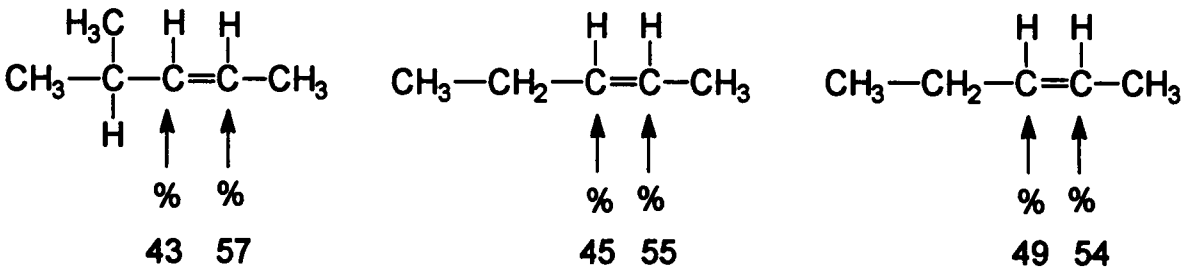
In the case of disubstituted terminal alkenes, $R_2C=CH_2$, the combined effect of two alkyl groups places the boron atom exclusively at the terminal position (Chart 3)

Chart 3



Disubstituted, internal alkenes undergo hydroboration with very low selectivity. Hydroboration of the *cis* and *trans* isomers of hydrocarbons produce negligible changes in orientation (1-3,40) (Chart 4).

Chart 4

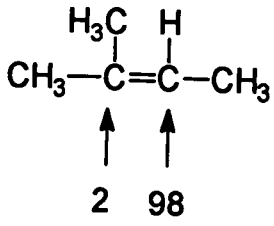


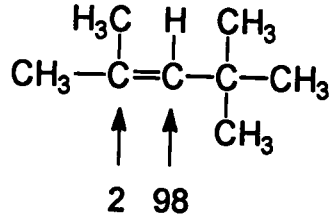
Trisubstituted olefins, $R_2C=CHR$, add boron 98% to the secondary carbon atom and only 2% to the tertiary carbon atom (Chart 5).

Finally, tetrasubstituted alkenes react with borane to give essentially a statistical distribution of boron at each position of the double bond (1-3,40).

The regioselectivity of the hydroboration reaction can be significantly

Chart 5





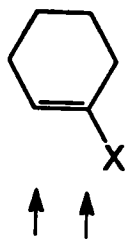
improved by employing bulky dialkylboranes as hydroborating agents (3,40,58,59,60). Thus, 1-hexene is hydroborated by Sia_2BH (58) and 9-BBN (59,60) to place the boron atom, 99% and 99.1% respectively, in the terminal position. Internal unsymmetrically substituted alkenes also exhibit high selectivity. Similarly, high selectivity was observed with cyclic and alicyclic internal alkenes. For example *cis*-4-methyl-2-pentene, on hydroboration with 9-BBN, showed 99.8% selectivity for the less substituted position as opposed to borane which gave a 57% selectivity. Similarly 3-methylcyclohexene, when hydroborated with 9-BBN, gave 80% boron addition at the carbon atom γ- to the methyl group as compared to the 50% observed with borane (40).

It is widely held that the increased selectivities observed with R_2BH reagents are due to the steric effect of the bulky alkyl groups. However, this is not an entirely satisfactory explanation since very simple dialkylboranes such as diethyl- and dipropylboranes, as well monoalkylboranes, add selectively to multiple carbon-carbon bonds (16).

1.1.4 *Directive Effects in Hydroboration of Functionalized Alkenes*

Although steric effects do not substantially change the direction of addition of boron to terminal alkenes, electronic effects (both inductive and mesomeric) exert a profound influence in this regard. Thus vinyl substituents with strong +M effects, such as OR (61,62) and NR_2 (63,64), cause boron to add to the β-position, whereas, substituents with -M effects like boron (65,66) and silicon (67-74), direct boron to the α-position, although the directive effect is weaker (Chart 6).

Chart 6

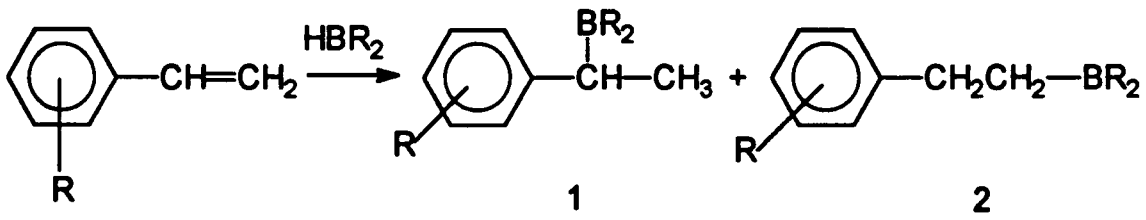


		X
100	0	NR_2
100	0	OEt
97	3	Me
60	40	OAc
40	60	Cl
10	90	$SiMe_2$

The significance of transmitted electronic effects is also demonstrated in the hydroboration of various substituted styrenes with borane (75,76). (Chart 7).

When steric effects and electronic effects directly oppose each other, the electronic effects dominate. For example, substituents with strong +M effects dominate the orientation of boron addition even over the steric influence of two

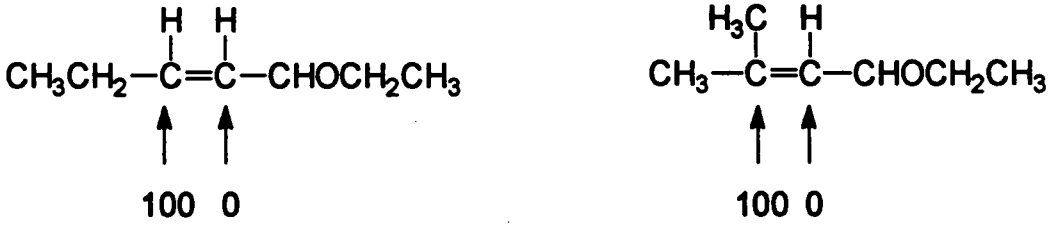
Chart 7



R	(1):(2)%		
	o	*m*	*p*
OH	14:86	19:81	7:93
Cl	26:74	30:70	27:73
CF_3	38:62	32:68	34:66
H		19 : 81	

attached β-methy groups (61) (Chart 8).

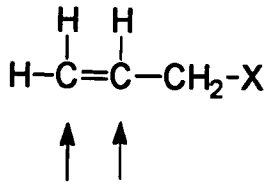
Chart 8



The significance of the inductive effects of the various substituents is most clearly evident in the hydroboration of allyl systems. In all systems studied the degree of ß-addition of boron increases with the electronegativity (-I) of the substituent (77,78) (Chart 9). Substitution of a methyl group at the γ position of the

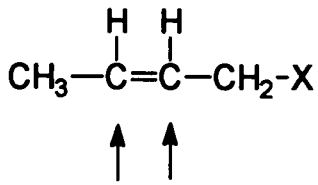
allyl system brings about a considerable enhancement in the addition of boron to the ß-position (Chart 10).

Chart 9



		X
3	97	SiMe
17	83	COOEt
19	81	OR
24	76	OH
35	65	OCOMe
40	60	Cl
45	55	Ts

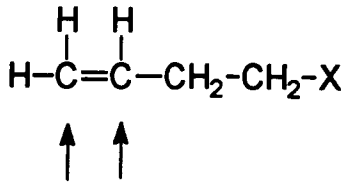
Chart 10



%	%	X
0	100	Cl
5	95	OCOMe
10	90	OH
16	84	OEt

When the substituent is positioned γ to an unsaturated carbon atom, a noticeable (11-18%) of the addition places boron at the internal position (79) (Chart 11).

Chart 11

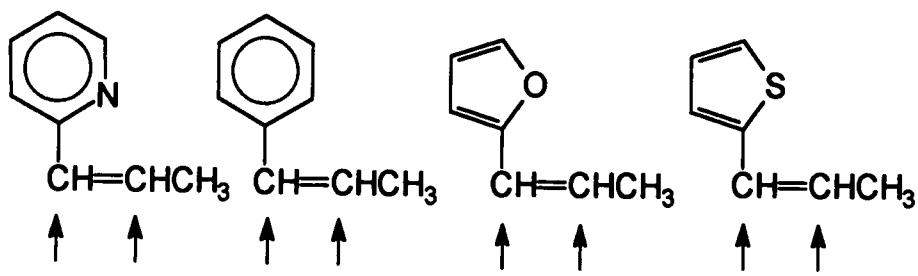


		X
93	7	H
89	11	OMe
86	14	OH
84	16	Cl

Finally, substituents located further from the double bond have negligible to no effect on the orientation of the addition of borane or dialkylboranes.

When the directive effect of a heterosubstituent is in direct competition with a methyl group, as in *trans*-methylethylene derivatives, the boron is directed predominantly α- to the heterosubstituent (Chart 12).

Chart 12

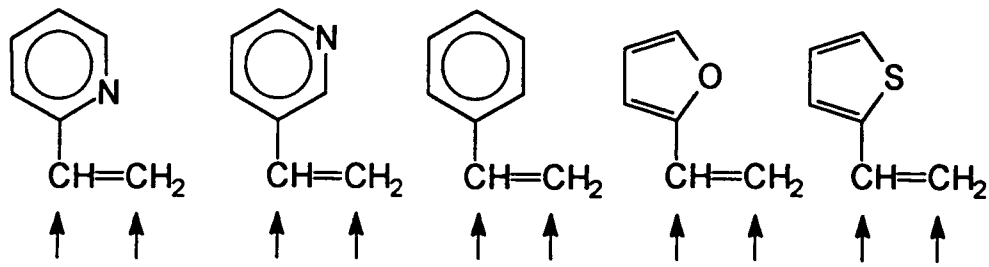


BH_3·THF	96	4	85	15	91	9	89	11
9-BBN	93	7	97	3	96	4	94	6
CHx_2BH	95	5			98	2	95	5
Sia_2BH	99	1			95	5	96	4

The directive effects of heterosubstituents, however, can be overcome by the employment of bulky, sterically demanding hydroborating agents such as 9-BBN,

Sia_2BH,and Chx_2BH. This can be deduced from the data in Chart 13 which lists styrene, 2-vinylfuran, 2-vinylthiophene and 3-vinylpyridine as representative cases (84-87).

Chart 13



BH_3 THF	67	33	50	50	19	81	16	84	12	88
9-BBN	37	63	8	92	2	98	3	97	2	98
CHx_2BH	83	17	23	77			0	100	0	100
Sia_2BH	85	15	17	83	2	98	0	100	0	100

1.2.1 *Dicarba-closo-dodecaboranes*

The discovery of dicarba-*closo*-dodecaboranes was first reported at the end of 1963 in both the United States and the USSR (84-87). One of the most surprising features of these compounds is the ability of the two carbon atoms and ten boron atoms to adopt the icosahedral geometry in which every carbon and boron atom is bound simultaneously to six other atoms (Figure 2). Of these, five are directed to vertices of a nearly regular pentagon while the sixth forms an exopolyhedral bond. This fact, coupled with the strong electron acceptor properties of the carborane cage and the steric hindrance which it creates, makes the study of C- functional derivatives of carboranes very interesting.

The ten boron and two carbon atoms of 1,2-carborane form an almost regular

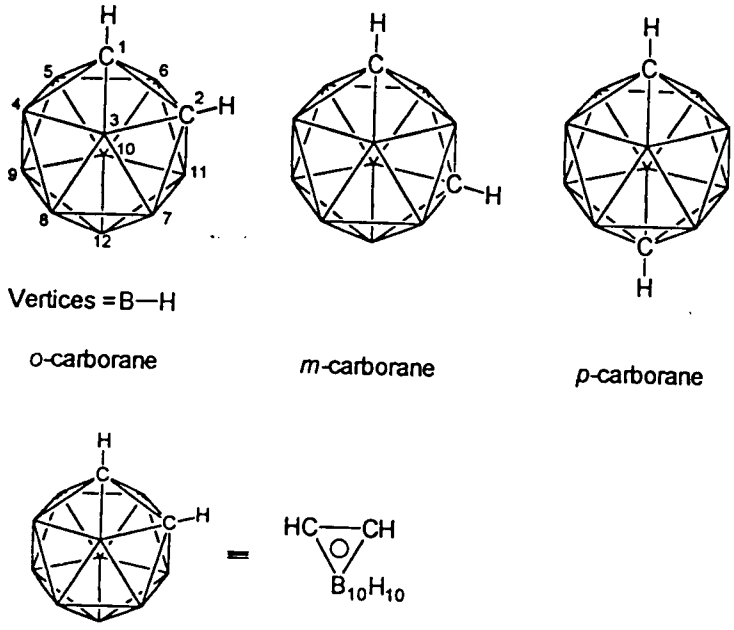


Figure 2. *o*-, *m*-, and, *p*-dicarba-*closo*-dodecaborane.

icosahedron, with the following interatomic distances: C-C = 1.62-1.70; B-C = 1.70-1.75; B-B = 1.70-1.79 Å. The B-C distance in carborane is longer than the B-C bond length in trimethylborane (1.578 Å) (88). C-H and B-H bonds, as well as the bonds of substituted carbon, C(2), and boron atoms, have normal-length σ bonds; the C-H bond length is 1.10 Å, and the C(2)-Me bond length is 1.53 Å.

o-Carborane is stable in the presence of most oxidizing agents, alcohols, and strong acids and possesses phenomenal thermal stability. Under an inert atmosphere it rearranges to *m*-carborane between 400 °C and 500 °C. This latter compound isomerizes to *p*-carborane between 600 °C and 700 °C (89,90).

One of the most important features of a carborane system is its ability to enter into substitution reactions at both the carbon and boron atoms. The reactivity at the carbon atom is due to the acidic character of the C-H bonds, as a result these

carbons can easily be metallated (89, 90).

Reactions that take place at the boron atoms of the cage include electrophilic halogenation (6,7), alkylation (6,7,91), sulfhydrylation (92) and metallation (91,94). These reactions are typical of aromatic compounds and, for this reason, the carborane molecule has been characterized as a "pseudoaromatic" system. The carborane cage has also been characterized as "superaromatic". This is because, in the carborane nucleus, 13 bonding molecular orbitals are filled by 26 electrons (6 from the two carbons and 20 from the 10 borons) (95,96).

According to ^{11}B NMR data and other physical methods, substitution at one atom of the carborane cage influences the overall charge distribution (89,90). Electrophilic substitution usually occurs first at the B(9),B(12) and then at the B(8),B(10) boron atoms of the *o*-carborane cage. The carbon atoms, and the adjacent boron atoms (3,6 and 4,5,7, and 11), do not appear susceptible to electrophilic substitution (89,90). The experimental results are in general agreement with theoretical calculations of the charge distribution (97,98) but they do not always correlate quantitatively.

The electron withdrawing effect of the carboranyl group has been studied in a number of ways; these include determinations of acid dissociation constants as well as various substituent constants (99-105). The acid strength of several *o*, *m*, and *p*-carborane- substituted carboxylic acids is moderately high; the pKa values range from approximately 2.5 to 6.5. The pKa values of the 1-HOOC-$C_2B_{10}H_{11}$ acids show that the electron-withdrawing power of the carboranyl isomers decreases in the series *o*-

>*m*->*p*-, in agreement with molecular orbital calculations (106). These results reveal that the separation of the carbon atoms in the carboranyl isomers (in the order *p*->*m*->*o*) lowers the localized electron deficiency in the region of the carbon atoms thus reducing the electron withdrawing ability of the carboranyl framework. Introduction of substituents having +I effects, such as alkyl, vinyl, and phenyl, onto the second carbon atom of the cage leads to a small decrease in the dissociation constant relative to the unsubstituted carboranecarboxylic acid (107). On the other hand, introduction of substituents having -I effects even as weak as a methoxymethyl group, leads to an increase in acidity relative to the unsubstituted acid (107). On the basis of the experimental pK_a values of carboranecarboxylic acids (108), hydroxycarboranes (109), mercaptocarboranes (110), and the basicity of aminocarboranes (111,112) sequences, the electron density increase on the atoms of the carborane units have been established. Electron density increases in the order B(1)= B(2) < B(3)=B(6) < (B(4)=B(5)=B(7)=B(11) < B(8)=B(10) < (B9)=(B12) for *o*-carborane, B(1)=B(7) < B(2)=(B3) < (B(5)=B(12) < B(4)=B(6)=B(8)=B(11) < B(9)=B(10) for *m*-carborane, and B(1)=B(12) < B(2)= B(3-11) for *p*-carborane. This irregular electron density distribution on the carborane vertices causes a difference in the electronic effects of the carboranyl group, depending on the position of the substituent on the carborane cage. The -I effect of the *o*-carboranyl group is much weaker when the substituent is attached at B(3) than when the bonding is to C(1). The effect also falls off sharply when the carboxy group is separated from the cage by methylene units (107).

The C- and B-carboranyl σ-constants were recently determined using physical organic methods (103,105,113). These are presented in the order of decreasing electron-withdrawing effects in Table 1. Hammett constants were determined using carboranylbenzoic acids in 75% ethanol. Inductive and resonance constants were determined by the Taft method using ^{19}F NMR chemical shifts of (fluorophenyl)carboranes in the equation $\delta_m^F = -7.10\sigma_I + 0.6$ and $\delta_p^F - \delta_m^F = 29.5\sigma_R^O$. In general, these studies indicate that C-carboranyl groups have a strong electron-acceptor effect which decreases in the order *o*- > *m*- > *p*-carborane. The electronic effects of the B-carboranyl group change according to the following sequence: the more remote the boron atom is from the carbon atoms in the carborane cage, the stronger are the electron donating effects of the B-carboranyl groups. Thus, 3-*o*- and 2-*m*-carboranyl groups are still electron acceptors, whereas 4-*o*-, 4-*m*, and 2-*p*-carboranyls are actually electroneutral. 9-*m*-Carboranyl and, in particular, 9-*o*-carboranyl groups clearly show electron-donating properties.

Recently it has been shown that the electron-withdrawing effect of the *o*-carboranyl group depends on the coordinating ability of the solvent used (124). Thus, in 1-(*p*-fluorophenyl)-*o*-carborane the σ_I values obtained varied from +0.400 in chloroform, which is a non coordinating solvent, to +0.26 in hexametapol, which is a strong electron donor solvent. The resonance effect (σ^o_R) remained constant. With 1-(p-fluophenyl)-2-methyl-*o*-carborane, on the other hand, the σ_I values were found to be practically solvent independent (σ_I= 0.39±0.04). Similarly, a substantial upfield shift in the fluorine NMR signal was observed in the spectra of 1-(*p*- and *m*-

fluorophenyl)-*o*-carboranes in coordinating solvents, compared to that observed in non-coordinating solvents. Fluorine chemical shifts measured in various solvents showed that, in 1-(*p*- and *m*-fluorophenyl)-2-methyl-*o*-carboranes, the electron-withdrawing ability of the 2-methyl-*o*-carboranyl group was solvent independent (124). Thus, it was concluded that the variation in the electron-withdrawing effect of the *o*-carboranyl group depends on hydrogen bond formation between basic solvents and the acidic hydrogen of the carbons in the *o*-carborane nucleus. Hydrogen bond formation increases the electronic density within the *o*-carborane nucleus and thus decreases its electron-withdrawing ability. The inductive electron-withdrawing effect of the 3-*o*-carboranyl group, σ_I, is also shown to be solvent-dependent and decreases in the following series: chloroform> carbon tetrachloride> methanol> tetrahydrofuran> dioxane, while its resonance effect, σ_R^o, is almost unchanged. The electron-withdrawing effect of the 3-(1,2-dimethyl)-*o*-carboranyl group, on the other hand, changes only negligibly in the solvents investigated,thereby, providing further support for the H-bonding hypothesis (124). Similar results have been obtained for the ^{19}F NMR chemical shifts of unsubstituted and cage carbon substituted fluoromethylated carboranes in various solvents (125). Thus, for 1-CH_2F-1,2-$C_2B_{10}H_{11}$ an upfield shift (≤3 ppm) is observed, ongoing from inert to donor solvents, whereas, for 1-CH_3-2-CH_2F-1,2-$CH_2B_{10}H_{10}$, $\delta^{19}F$ is practically the same in all solvents. On the basis of nitration experiments, ^{19}F-NMR and pK_a

Table 1. σ-Constants of *o*-, *m*-, and *p*-Carboranyl Groups (113-123).

	inductive and resonance constants		Hammett constants	
position of substituent	σ_I	σ_R^o	σ_p	σ_m
1-*o*	0.375	0.003	0.46	0.47
1-*o*	0.380	0.0	0.43	0.49
1-*m*	0.21	-0.05		
1-*m*	0.194	-0.039	0.33	0.25
1-*p*	0.14	-0.002		
2-*m*	0.12	-0.05	0.15	0.14
3-*o*	0.11	0.07	0.19	0.19
3-*o*	0.01	0.06		
2-*p*	0.02	0.02		
4-*o*	-0.04	0.02	-0.05	-0.03
4-*m*	-0.04	0.02	0.02	0.02
9-*m*	-0.12	-0.02		
9-*o*	-0.16	-0.03		
9-*o*	-0.23	-0.02		

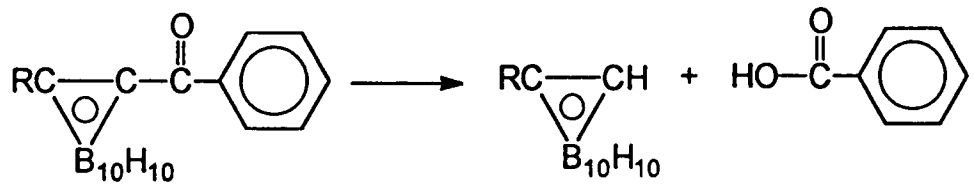
data, Hawthorne and coworkers (90) have concluded that: (a) the *o*-carborane system is strongly electron-withdrawing by an inductive mechanism, the -I effect being comparable to the halogens; (b) there is not appreciable ground state extension of electron delocalization by interaction of an aryl group with the *o*-carborane unit; and (c) weak ground state extension of electron delocalization by interaction of an aryl group with the *m*-carborane moiety may come about via electron donation from the *o*-carborane unit.

A number of studies of ^{35}Cl and ^{79}Br quadruple resonance (NQR) spectra of *p*-chloro- and *p*-bromophenyl carboranes have shown that the carboranyl cage, as a substituent on the benzene ring, is an electron acceptor and one which is stronger than F, Cl or COOH but weaker than the NO_2 group (126).

Furthermore, it has been shown that the transmission of substituent effects through the carborane cage for 1- and 2-substituted compounds is greater than the transmission through an aromatic nucleus. Thus, the difference in the ^{35}Cl NQR frequencies between chloro and *p*-dichlorobenzene ($\Delta\nu$ = 0.117) and 1-CH_2Cl-1,2-$C_2B_{10}H_{11}$ and 1,2-$(CH_2Cl)_2C_2B_{10}H_{10}$ ($\Delta\nu$ = 1.061) demonstrates that the effect of one chlorine atom on the other is greater in the latter set of compounds (126).

There is also experimental evidence which demonstrates the potent electron-withdrawing properties of the carboranyl cage (89). It was found that carboranyl ketones, alcohols, esters and acids in which the functional group is attached to the carborane cage, undergo cleavage of the C-C bond between the carboranyl group and the substituent when exposed at room temperature to catalytic amounts of sodium

ethoxide in absolute ethanol, sodamide in liquid ammonia, and aqueous or alcoholic ammonia. Basic alumina was also shown to cleave the C-C bond in 1-phenyl- and 1-alkyl-*o*-carboranyl ketones during chromatographic purification (127) (eq. 18).



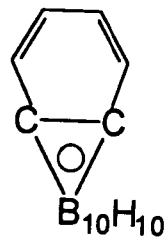
(18)

Similarly, cleavage was also observed in the reactions of *o*-carboranylketones with phenyllithium, *n*-butyllithium, and phenylmagnesium bromide in THF (89). Moreover, the reaction of $LiAlH_4$ with bis(1-phenyl-*o*-carboranyl)ketone and bis(1-phenyl-*o*-carboranyl)ketone does not result in reduction of the carbonyl group but, instead, cleavage of the C-C bond is observed (89).

Despite all the evidence supporting the -I effect of the *o*-carborane cage, the relationship between inductive and resonance effects and the problem of potential carborane aromaticity are still under discussion. Hoffmann's and Lipscomb's prediction of conjugation between a *p*-orbital on a π substituent attached at C(1) of the cage and a surface orbital of the polyhedron has been difficult to prove experimentally (128). However, the results from UV (129) and Raman (130) spectroscopy of phenylcarboranes indicated that the carborane nucleus does not change the π-electron levels of an attached benzene ring. Only an inductive effect is observed. Furthermore, the barriers to rotation of dimethylamino groups in 1,2-bis-(*N,N*-dimethylcarbamoyl)-*o*-$C_2B_{10}H_{10}$ and 1,7-bis(*N,N*-dimethylcarboranyl)-*o*-

$C_2B_{10}H_{10}$ (ΔG = 13.1 Kcal/mol at -17 °C and 12.8 Kcal/mol at -17 °C, respectively) have been attributed to π-bonding of the carbonyl carbon with the carborane cage (131). This was considered a measure of the aromaticity of the carboranyl group.

Matteson showed that the benzocarborane shown below exhibited a small amount of aromatic character based on ^1H NMR data, in spite of the long carbon-carbon bond along the shared edge (~1.65Å) and the weakness of π-bonding between the carboranyl group and external groups (129).



The lack of chemical reactivity of benzocarborane towards electrophilic reagents like sulfuric acid and bromine is also consistent with aromaticity. The results noted above do not clarify the situation completely because it is difficult to differentiate the inductive effect of the cage from resonance effects (129).

Recently, Wu and Jones synthesized a carbon-to-boron bridged benzocarborane (132). ^1H NMR data led them to conclude that ring-cage conjugation could play an important role in this system.

One of the most important reactions in carborane chemistry was reported by Wiesboeck and Hawthorne in 1964 (133). They showed that *o*-carborane can be

degraded using alcoholic alkali removing the B(3) atom and forming the 1,2-dicarbaundecaborate(1-) ion (eq. 19).

$$o\text{-}C_2H_2B_{10}H_{10} + CH_3O^- + 2CH_3OH \rightarrow C_2B_9H_{12}^- + H_2 + B(OCH_3)_3 \qquad (19)$$

Similar cleavage reactions can be induced by ammonia, *n*-butylamine, diethylamine, and triethylamine in alcoholic solvents. In general C-substitution on the carborane cage facilitates such cleavage (134). Starting from this anion, Hawthorne et al. obtained a number of "sandwich" derivatives which are analogues of the transition metal cyclopentadienide complexes (135).

Finally, studies have shown that C-alkenyl derivatives of *o*-carboranes containing an *o*-carboranyl group adjacent to the double bond are far less reactive than most alkenes towards electrophiles. Early investigators failed to note any reaction of bromine with 1-vinyl, 1-isopropenyl, or 1-allyl-2-methyl-*o*-carborane (89,90). It has since been shown that 1 mole of bromine slowly adds to 1-vinyl-*o*-carborane in CCl_4 over a very long period (150 h) at 20 °C, and in less time (2 h) at the boiling point of the solvent (89). Similarly, no reaction of 1-vinyl-, 1-isopropenyl or 1-allyl-2-methyl-*o*-carborane is observed with hydrogen peroxide, peracetic acid, hypochlorous acid or iodine monobromide in glacial acetic acid (89). Trifluoroperacetic acid does attack both 1-allyl- and 1-isopropenyl-*o*-carborane, forming stable epoxides (89). In contrast, the reaction of 1-homoallyl-*o*-carborane with trifluoroperacetic acid forms a glycol trifluoroacetate adduct (89). Acid catalyzed opening of an epoxy ring is evidently inhibited by an *o*-carboranyl group when it is adjacent to the cage, but not when it is insulated from the cage by

methylene groups as in the homoallyl derivative. Thus alkenyl double bonds that are separated from the *o*-carboranyl cage by methylene or other insulating groups react more or less normally with electrophilic reagents. Thus bromine in CCl_4 adds readily to 1-homoallyl-*o*-carborane to produce the corresponding dibromobutyl derivative (89).

In the past year, Jones and co-workers (136) discovered a route to the 1,2-didehydro-*o*-carborane which can be considered a carborane version of dehydrobenzene. Transformations of this intermediate present new evidence for the aromatic character of a new carborane molecule.

1.2.1 *NMR Studies of Dicarba-closo-dodecaboranes*

The NMR behaviour of ^{11}B nuclei located in borane frameworks shows so many irregularities that the ^{11}B chemical shifts have not been generally used as an identification tool. However, two effects which are well documented are the antipodal shift effect and the vicinal shift effect (137). The antipodal shift, δA, arises from the presence of a substituent X on a borane framework which causes a shift of the antipodal (opposite) boron atom to higher field. The shift has been postulated to be proportional to the electron donating ability of the substituent X. Such shifts have been correlated with the ^{13}C chemical shift of the *para*-position in monosubstituted benzenes and a parallelism, but not identity, between antipodal and +M mesomeric effects was suggested. The influence of the substituent is transferred in the borane framework not only from boron to boron but also from carbon to an antipodal boron.

The vicinal shift effect arises from the presence of a substituent X on a borane framework and causes a shift of the vicinal (*ortho*) B atoms to a lower field. This shift has been suggested to be proportional to the Sanderson electronegativity of X.

The proton decoupled, B-11{H-1}, ^{11}B NMR spectrum of *o*-carborane shows 4 signals of relative intensities 1:1:2:1 at chemical shifts, relative to $BF_3{\cdot}O(C_2H_5)_2$ of -2.0 -9.1, -13.9 and -15.3 ppm (CS_2). The assignment of these signals, inferred from MO theory, is shown in Table 2 (98).

The results indicate that chemical shielding of the boron atoms increases with

Table 2
^{11}B NMR Chemical Shifts (ppm) of *o*-$C_2B_{10}H_{12}$

Atom	Chemical Shifts (11M)	Charge
C-1 = C-2	---	+0.29
3 = 6	-15.3	+0.26
4 = 5 = 11= 7	-13.9	-0.02
8 = 10	- 9.1	-0.28
9 = 12	- 2.0	-0.24

decreasing electronegativity of the given atom. This is unusual, because in most cases the chemical shielding of the observed nucleus decreases as its electronegativity decreases. The ^{11}B NMR spectrum of 8-Br-*o*-$C_2B_{10}H_{11}$ is summarized in Table 3 and clearly indicates the antipodal shift effect on B(6) as well as the vicinal shift effect on B(3), B(4,7) and B(9,12) (relative to *o*-$C_2B_{10}H_{12}$) (138).

The ^1H NMR spectra of carborane derivatives are more difficult to evaluate than the corresponding spectra of organic compounds. This difficulty arises because

the spectra display the ^{11}B-^{1}H coupling constants in the same order of magnitude as the ^{1}H chemical shifts. Since, for the ^{11}B nucleus I=3/2, there are four possible spin states (i.e. +3/2, +1/2, -1/2, -3/2) and coupling with each state occurs with an equal probability, the ^{1}H NMR resonance for the terminal hydrogen atoms splits into a 1:1:1:1 four line multiplet. The considerable broadening of the polyhedral proton signals due to partially relaxed coupling between proton and boron, in addition to the large ^{11}B-^{1}H coupling constant of 150 Hz, render the high field region of the ^{1}H

Table 3

^{11}B NMR Chemical Shifts (ppm) of
o-$C_2B_{10}H_{12}$ and 8-Bromo Derivative

Atom	*o*-$C_2B_{10}H_{12}$	8-Br-*o*-$C_2B_{10}H_{11}$
B-11 3	-15.3	-12.9
4	-13.9	-11.5
5	-13.9	-12.7
6	-13.9	-17.9
7	-13.9	-11.5
8	- 9.1	- 4.0
9	- 2.0	+ 0.3
10	- 9.1	- 8.6
11	-13.9	-12.7
12	- 2.0	+ 0.3

NMR spectra of carborane compounds of little help in structural identification.

The 400 MHz ^{1}H NMR spectrum of *o*-$C_2B_{10}H_{12}$ carborane shows four broad, poorly defined peaks between 1.4 and 3.0 ppm due to boron-bound, hydrogen atoms.

The proton signals of the polyhedral C-H groups were shown to be strongly solvent dependent and their shielding in various solvents are summarized in Table 4 (139).

A number of ^{13}C NMR studies have been carried out in order to obtain information on the possible electronic surroundings of the carbon atoms in the carborne polyhedron. Interpretation of the results, however, has been difficult. Table 5 contains the chemical shifts of the ^{13}C nuclei, relative to TMS, in the of *o*-, *m*-, and *p*- icosahedral carboranes. It is evident that the shielding of the ^{13}C nuclei decreases in the series *o*->*m*->*p*-, which suggest that the carbon atom in *p*-carboranes possesses a larger effective positive charge than in *o*- and *m*- carboranes. However, this idea contradicts Lipscomb's (106) studies which show that the partial positive charge on the carbon increases in the order *p*- < *m*- < *o*-. The coupling constants for the C-H bond, however, showed some correlation with the decrease of the positive charge on carbon atom of the cage. For example, the charge on the carbon atom in carboranes decreases in the series *o*-> *m*-> *p*- carboranes. The coupling constant J_{C-H} in THF varied as follows: 206 Hz *o*-, 190 Hz *m*-, 177 Hz *p*. The data in Table 5 also show that an increase in the polarity of the solvent results in a deshielding of the carbon signal, with the largest change (3 ppm) occurring with the most polar molecule, *o*-carborane (139).

In general, when the hydrogen atom of a polyhedral C-H moiety of a carborane is substituted by a group containing a carbon, nitrogen, or oxygen, the carborane carbon resonance is deshielded. This is clearly shown for the *o*-carborane

Table 4
^{1}H NMR Chemical Shifts of the C-H Exopolyhedral Hydrogen Atoms of *o*-$C_2B_{10}H_{12}$ Relative to TMS

Solvent	δH (ppm)
DMSO	4.580
Acetone	4.220
$CHCl_3$	3.378
$S(CH_3)_2$	3.695
THF	3.882
C_6H_6	2.113
CH_2Cl_2	3.582

Table 5
Chemical Shifts of ^{13}C NMR Signals in Isomeric $C_2B_{10}H_{12}$

Solvents	*o*-	*m*-	*p*-
DMSO	56.5	56.5	64.1
THF	55.5	56.2	64.2
Acetone	55.8	56.8	64.6
CH_2Cl_2	55.1	56.1	64.3
$CHCl_3$	54.6	55.2	63.6
CCl_4	53.2		

in Table 6. These data further illustrate that, for *o*-carboranes, an increase in the electron-withdrawing ability of the carbon atom bearing the substituent results in a deshielding perturbation of the ^{13}C NMR resonance of the adjacent carbon atom. The effect is also shown in the data summarized in Table 7.

In the case of 1,2-$(CH_3)_2$-*o*-$B_{10}H_{10}C_2$ for example, the polyhedral carbons are deshielded (relative to *o*-$C_2B_{10}H_{12}$) by the directly bonded methyl group as well as the methyl group on the adjacent carbon. The methyl-substituted polyhedral carbon atom of 1-CH_3-*o*-$C_2B_{10}H_{11}$ is less (Table 6) deshielded because the adjacent carbon has a hydrogen substituent. Comparison of the ^{13}C resonances results with those of related aliphatic and aromatic molecules shows that the $\Delta\delta c$ values of *o*-carboranes more closely resemble the aliphatic model systems. This suggests that the substituents most probably interact with the icosahedral carborane cage mainly by an inductive mechanism (139).

Finally, the antipodal shift discussed in the ^{11}B NMR spectra is also observed in the ^{13}C NMR spectra. The influence of substituents is transferred in the polyhedral borane frameworks not only from boron to boron but also to other antipodal atoms such as carbon or phosphorus. For example, when a substituent is on the boron atom of the cage opposite to a carbon (as in 9-Br-*o*-$C_2B_{10}H_{11}$), C(1) of the cage (which is *meta* to the substituent) resonates at 54.6(CS_2), whereas, the antipodal carbon C(2) resonates upfield at 48.1 ppm (139).

Table 6
^{13}C Chemical shifts of the Polyhedral Carbon Atoms
of 1-R-*o*-$C_2B_{10}H_{11}$ Derivatives in Acetone

R Group	CR	CH
H	56.9	56.9
$Si(CH_3)_3$	65.0	60.9
CO_2CH_3	69.9	58.8
CO_2H	70.7	59.0
CH_3	71.5	62.9
CH_2Br	72.8	62.9
$CH=CH_2$	74.6	61.4
COC_6H_5	77.0	60.3
C_6H_5	77.7	61.4
NH_2	92.3	69.5

Table 7

^{13}C Chemical Shifts of the Polyhedral Carbon Atoms of

R_2-*o*-$C_2B_{10}H_{10}$ Derivatives

Substituent	δc(ppm)
SCH_3	73.9
CH_3	74.6
$Si(CH_3)_3$	76.3
C_6H_5	86.5

1.2.2 *Mass Spectroscopy of Dicarba-closo-dodecaboranes*

Mass spectroscopy is used extensively in carborane chemistry both as a means of detection and as a simple substitute for elemental analysis (140). Boron compounds subjected to electron impact and then analyzed mass spectrometrically display a polyisotopic mass spectrum of essentially statistically distributed ^{11}B and ^{10}B. The concentrations of all the isotopic species in a particular ion group $^{11}B_x{}^{10}B_y$ is given by

$$[^{11}B_x{}^{10}B_y] = W\ (.80)^x(.20)^y$$

In this expression, W is the statistical weight, the number of different ways ^{11}B and ^{10}B atoms can be arranged in the available skeletal position, and is numerically equal to (X+Y)/X!Y!. For ion groups containing a small number of borons ($B_1{}^+$ to $B_4{}^+$), the spectral profile is statistically weighted in favor of the higher mass numbers

of the group because of the high concentration (80%) of ^{11}B. As the number of borons increases beyond four, the maximum intensity peak begins to shift away from the cut-off peak. In the B_{10} ion group, for example, $^{11}B_8{}^{10}B_2{}^+$ is 2.81 times as abundant as $^{11}B^+{}_{10}$ (Table 8). Similar abundance ratios can be calculated for all other ions groups such as B_9, B_8, B_7 etc. If C_2H_{12} were added to the boron ion species in Table 8, the cut-off peak would shift upward by 36 a.m.u. and the spectral profile would be the same as that of elemental boron. Thus $C_2B_{10}H_{12}{}^+$ would occupy the regime from 136 to 146 (ignoring ^{13}C contributions) corresponding to the mass range of $C_2{}^{10}B_{10}H_{12}{}^+$ to $C_2{}^{11}B_{10}H_{12}{}^+$. The highest intensity peak would be m/z 144 because the species $C_2{}^{11}B_8{}^{10}B_2H_{12}{}^+$ would be statistically most probable. However, since electron impact also knocks hydrogens off some of the *o*-carborane molecules, complete analyses can be done only with the use of computers. Such analyses show that the main fragmentation pathway of the molecular ion, M^+, is the dehydrogenation process. Cleavage of the carborane framework proceeds only to a negligible degree. The maximum peak represents the $[M-2H]^+$ ion resulting from the elimination of a hydrogen molecule from the molecular ion and a H atom from the ion $[M-H]^+$. However this can vary, depending upon the temperature of the ionization chamber.

Addition of methyl, ethyl and other substituents to the carborane cage at the carbon atom merely shifts the cut-offs upward by the corresponding mass increase. The fact that the parent group profile is changed only slightly suggests that the hydrogen abstraction upon electron impact occurs preferentially on the borane

Table 8

Polyisotopic Mass Distribution of a Ten boron Species

Isotopic Species	Abundance Ratio
$^{11}B_{10}$	1.00000
$^{11}B_9{}^{10}B_1$	2.49970
$^{11}B_8{}^{10}B_2$	2.81210
$^{11}B_7{}^{10}B_3$	2.10910
$^{11}B_6{}^{10}B_4$	0.92260
$^{11}B_5{}^{10}B_5$	0.27670
$^{11}B_4{}^{10}B_6$	0.05705
$^{11}B_3{}^{10}B_7$	0.00815
$^{11}B_2{}^{10}B_8$	0.000843
$^{11}B_1{}^{10}B_9$	0.0000562
$^{10}B_{10}$	0.0000107

skeleton, not the side chain. With ethyl and methyl side chains, this has been verified by mass spectral analyses of compounds containing deuterated alkyl groups (141).

1.3 *Statement of the problem*

Since organoboranes are among the most versatile intermediates available to the organic chemist and undergo a variety of synthetic transformations, the synthesis of organoborane intermediates carrying the carborane nucleus is highly desirable. However, the organoborane intermediates must be free of isomers to provide maximum synthetic utility. Thus, the regioselectivity of addition of representative hydroborating agents such as borane-tetrahydrofuran (BH_3·THF), borane-methyl sulfide (BMS), 9-borabicyclo[3.3.1]nonane (9-BBN) and dicyclohexylborane (Chx_2BH) to a variety of 1-alkenyl-*o*-carboranes is important and is the subject of this study. The olefins selected for the study were: 1-vinyl-*o*-carborane (**1**), 1-isopropenyl-*o*-carborane (**2**), *trans*-1-propenyl-*o*-carborane (**3**), 1-allyl-*o*-carborane (**4**), 1-allyl-2-hexyl-*o*-carborane (**5**), 1-crotyl-*o*-carborane(**6**), 1-homoallyl-*o*-carborane (**7**), 1-homoallyl-2-methyl-*o*-carborane (**8**), 1-(4-pentenyl)-*o*-carborane (**9**), and 1-(7-octenyl)-*o*-carborane (**10**). The syntheses of these alkenyl-*o*-carboranes are discussed in chapter II. In these olefins, the *o*-carboranyl group is systematically removed from the double bond in order to best evaluate its effect on the hydroboration reaction. Thus olefins **1**, **2**, and **3** contain a double bond α-to the cage, olefins **4**, **5**, and **6** contain a double bond ß- to the cage, and olefins **7**, **8**, **9**, and **10** contain a double bond remote from the cage. The hydroboration reactions are discussed in Chapters

III, IV, and V.

There are several points of interest in this study: (a) the reaction rates; (b) the stability of the organoborane intermediates; (c) evidence of complexation of the cage with either the borane reagents or the exopolyhedral boron in the intermediates; (d) the effect of the solvent on the regioselectivity of hydroboration; (e) the effect of an alkyl substituent on the C(1) atom of the carborane cage on the reactivity and regioselectivity of addition; (f) the composition and distribution of the intermediates; (g) the ratio of the isomeric alcohols produced after oxidation; and (h) the stability of the carborane cage under the alkaline conditions employed in the oxidation step. In this regard the oxidation was carried out using two oxidizing agents: alkaline sodium peroxide (H_2O_2/OH^-) and sodium perborate ($NaBO_3$). The oxidations were examined using equimolar as well as excess amounts of oxidizing agents.

The progress of these reactions was studied by ^{11}B NMR, ^{1}H NMR, and ^{13}C NMR. In the hydroboration of **1** with borane, no signals due to any boron intermediates were detected in the ^{11}B NMR. For this reason the reaction was studied with 1:1, and 3:1 molar ratios (olefin:borane) in order to obtain a better understanding of the intermediates formed in the reaction.

CHAPTER II

Synthesis of 1-Alkenyl-*o*-carboranes and 1-Alkenyl-2-alkyl-*o*-carboranes.

2.1 *Introduction*

The icosohedral carborane compounds and their nido salts are widely used in industry (142,143), research laboratories (137,144), and medicine (145). Despite the great utility of these carborane compounds, there are only three synthetic methods of rather limited utility leading to carbon substituted carboranes. Two were developed earlier (84,85,146,147) and one recently by Hawthorne (148).

The first method involves the reaction of acetylenes with complexes prepared from decaborane and Lewis bases such as acetonitrile, alkylamines, and alkyl sulfides (84,85) (eqs. 20 and 21).

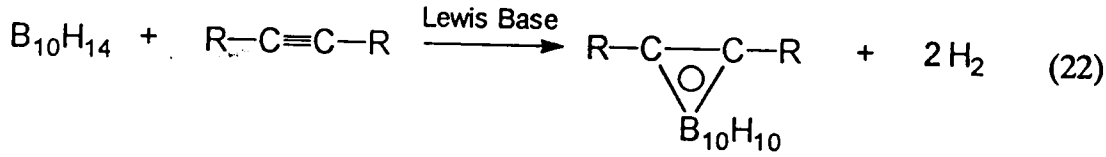
$$2B_{10}H_{14} + 4L \rightarrow 2B_{10}H_{12}\cdot L_2 + 2H_2 \qquad (20)$$

$$2B_{10}H_{12}\cdot L_2 + 2HC{\equiv}CR \rightarrow 2HCB_{10}H_{10}CR + H_2 + 4L \qquad (21)$$

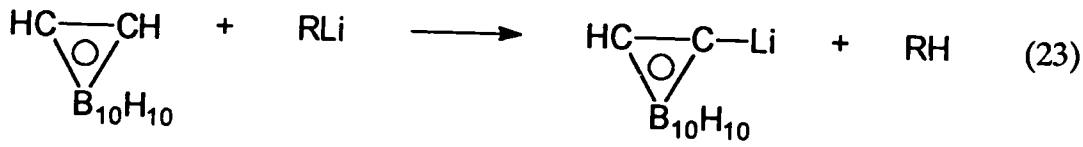
$L = CH_3CN, Alk_3N, Alk_2S$

Since the isolation of the bis(ligand) decaborane species is unnecessary, the carborane preparation is more conveniently carried out between decaborane and the alkyne in the presence of the Lewis base (eq 22).

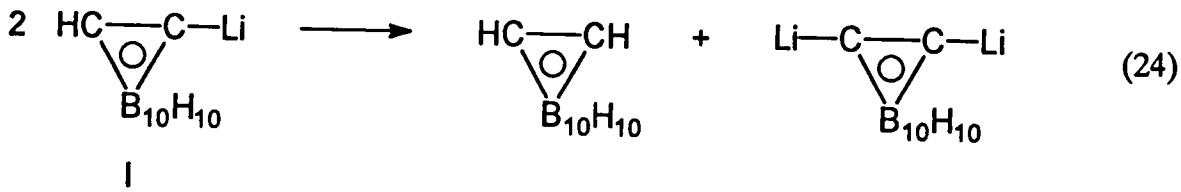
The second approach involves the metallation of the *o*-carborane C-H group, followed by treatment with a variety of reagents, to yield mono- and di-C-functional



o-carborane (148-150). The metallation reaction is facilitated by the strong electron-withdrawing character of the *o*-carborane unit. Organolithium derivatives of carboranes are readily obtained by the action of *n*-butyllithium (148), or phenyllithium (149,150), either on carborane itself (eq 23) or on the mononalkyl- and monoarylcarboranes.



The reaction is usually carried out by treating the carboranes with a benzene solution of *n*-butyllithium at 60-80 °C (148). The syntheses of a mono-C-substituted *o*-carborane is difficult due to the disproportionation of monolithio-*o*-carborane which leads to the undesired di-C-substituted product (eq 24) (89,90).



To obtain the monolithium derivative of *o*-carborane, the reaction must be conducted in ether at 0 °C and the solution of *n*-butyllithium (or phenyllithium) added to the *o*-carborane in such a manner that excess of the latter is present throughout the reaction (146). In contrast, the addition of an ethereal solution of *o*-carborane to excess *n*-butyllithium at 0-15 °C results in a good yield of dilithiated carborane (146). The synthesis of the sodium derivatives of *o*-carboranes, by the action of sodamide, was developed by Zakharkin *et al.* (149). This reaction was extended to the amides of other metals (lithium, potassium, calcium) (84,150). In contrast to the reactions with lithiumalkyls and metal amides, the hydrogen atoms attached to the carbon atoms of the carborane cage are not replaced by a metal atom on treatment with organomagnesium and organozinc compounds in ethereal media. The reaction proceeds only when complexing solvents are used. Thus, ethylmagnesium bromide reacts smoothly with *o*-carborane and alkyl-*o*-carboranes (147) in tetrahydrofuran, and diethylzinc reacts with phenyl-*o*-carborane in hexamethylphosphoramide (151).

Successful preparations of some carborane derivatives under phase transfer catalysis conditions have also been reported. Zakharkin *et al.* (152) have obtained 1-alkyl- and 1,2-dialkyl-*o*-carboranes by alkylating *o*-carborane and 1-methyl- or 1-phenyl-*o*-carborane with alkyl halides in THF (or DMSO) systems using dibenzo-18-crown-6-ether and sodium hydroxide .

The third method developed by Hawthorne *et al.* (148) involves the protection of the carbon atom of *o*-carborane by *tert*-butyldimethylsilyl (TBDMS) group (153).

The protecting effect of TBDMS is based on its ability to react only with the monolithio component of the equilibrium mixtures (eq 24) and on the further facile removal of the protecting group in the deprotection step. Other protecting groups such as Me_3Si and PhS were attached to the carborane cage, but were easily displaced by *n*-BuLi in the subsequent step (148).

2.2 *Results and Discussion*

The alkenyl carboranes synthesized in this study are listed in Table 9. The synthesis of **4, 6, 7, 9, 10** was carried out, as described by Hawthorne (148), whereas alkenes **2, 3, 5,** and **8,** were synthesized as it is described below. The synthesis of **9** is described first as a representative case of Hawthorne's method.

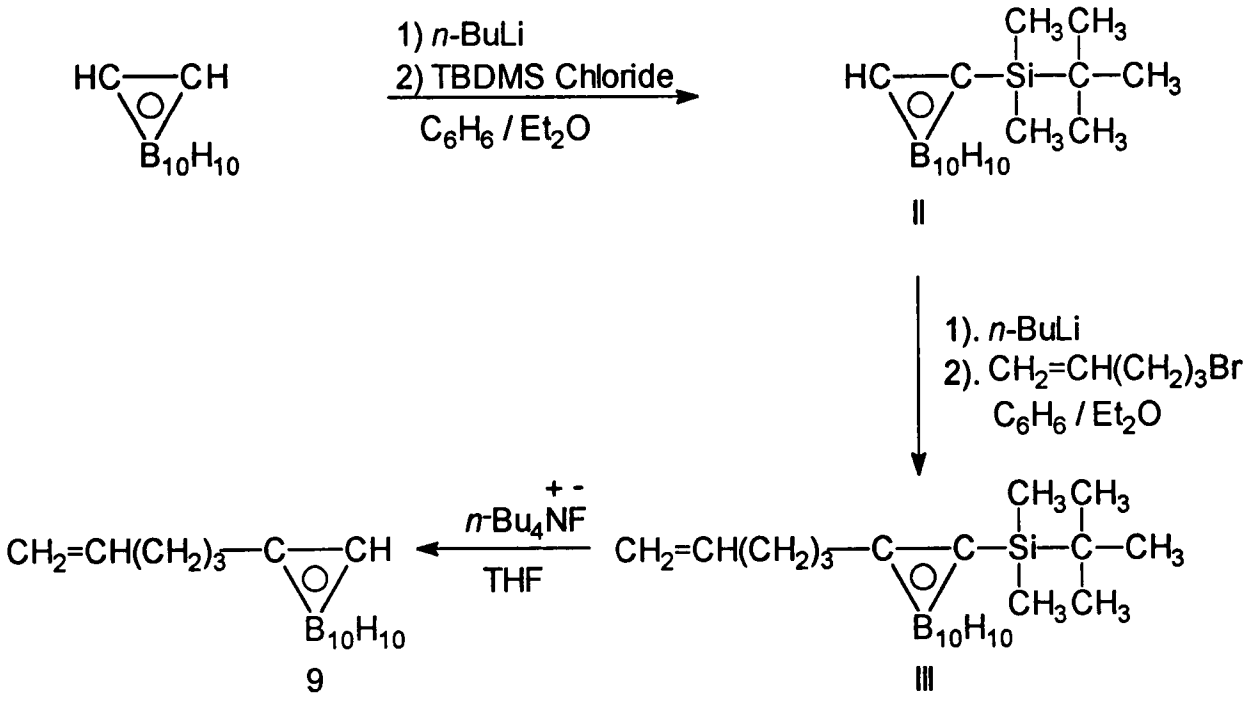
The reaction of *o*-carborane with one equivalent of *n*-BuLi at 0° C in a 2:1 C_6H_6/Et_2O solvent mixture established the equilibrium shown in eq 24. The monolithiated component (**I**) of this equilibrium then reacted with 1.1 equiv of *tert*-butyldimethylsilyl chloride (TBDMSCl) at 40 °C to produce the mono-silylated derivative of *o*-carborane (**II**) in 90% yield (Scheme 1). **II** was isolated, purified by sublimation at 72° C, distilled at 118 °C and characterized. The mass spectrum of **II** revealed an intense peak in the polyisotopic spectrum at 243 amu with a high mass cut-off peak at 245 amu due to the loss of a methyl from the molecular ion at 260 amu. The ^1H NMR spectrum contains a singlet at δ 1.05 due to the *t*-butyl group, a singlet at δ 0.30 due to the two methyl groups, and another singlet at δ 3.28 due to the cage C-H acidic proton. The ^{11}B NMR spectrum exhibited six resonances in a 1:1:2:2:2:2 ratio extending from δ 0.05 to -2,09.

Table 9. 1-Alkenyl- and 1-Alkenyl-2-alkyl-*o*-carboranes Synthesized in this Work.

Structure	Name
$HCB_{10}H_{10}CCH=CH_2$	1-Vinyl-*o*-carborane (**1**)[a]
$HCB_{10}H_{10}CC(CH_3)=CH_2$	1-Isopropenyl-*o*-carborane (**2**)
$HCB_{10}H_{10}CCH=CHCH_3$	*Trans*-1-propenyl-*o*-carborane (**3**)
$HCB_{10}H_{10}CCH_2CH=CH_2$	1-Allyl-*o*-carborane (**4**)
$C_6H_{13}CB_{10}H_{10}CCH_2CH=CH_2$	1-Allyl-2-hexyl-*o*-carborane (**5**)
$HCB_{10}H_{10}CH_2CH=CHCH_3$	1-Crotyl-*o*-carborane (**6**)
$HCB_{10}H_{10}CCH_2CH_2CH=CH_2$	1-Homoallyl-*o*-carborane (**7**)
$CH_3CB_{10}H_{10}CCH_2CH_2CH=CH_2$	1-Homoallyl-2-methyl-*o*-carborane (**8**)
$HCB_{10}H_{10}C(CH_2)_3CH=CH_2$	1-(4-Pentenyl)-*o*-carborane (**9**)
$HCB_{10}H_{10}C(CH_2)_6CH=CH_2$	1-(7-Octenyl)-*o*-carborane (**10**)

[a]Purchased from Dexsil corp.

Scheme 1



II was treated with an additional 1.1 equivalents of *n*-BuLi in 2:1 C_6H_6/Et_2O which was followed by 1.3 equivalents of 5-bromo-1-pentene. This solution was left to stir at 35 °C for 24 h to afford **III**. The final step in this synthesis was deprotection of **III** by treatment with $Bu_4N^+F^-$ in THF (-78 °C to 0 °C) for 30 min to afford **9** in 78% yield. **9** was characterized by ^{11}B, ^{13}C and ^1H NMR spectroscopies. The C/H COSY spectrum of **9** is shown in Figure 3. The resonance at δ 60 in the ^{13}C domain, due to the C-H carbon of the cage, cross correlates with the broad singlet at δ 3.1 in the ^1H domain. A summary of the overall yields realized in the syntheses of the 1-alkenyl-*o*-carboranes by Hawthorn's method is shown in Table 10.

The low yields in these syntheses were mainly due to significant amounts of cage degradation products formed during the deprotection step. All of the *nido*-

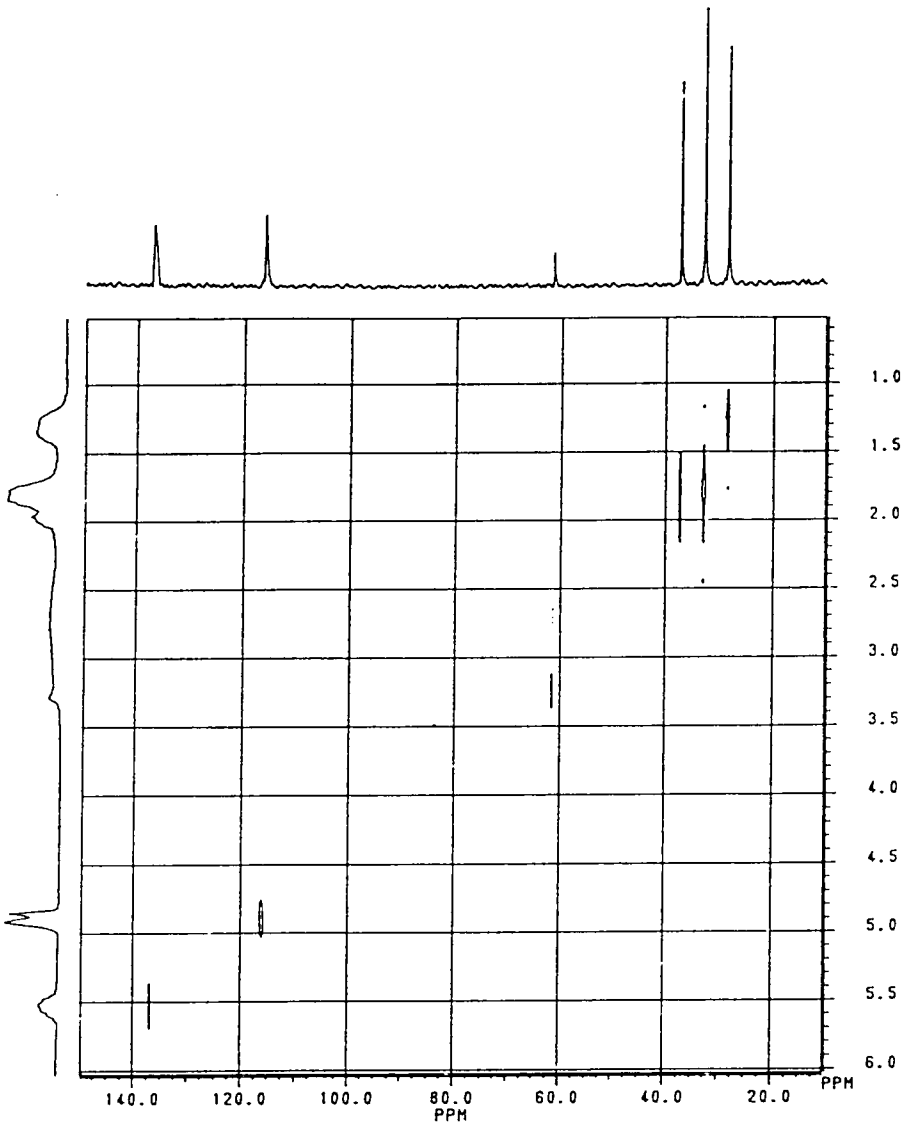


Figure 3. C/H COSY NMR spectrum of 1-(4-pentenyl)-*o*-carborane (**9**)

Table 10. Purified Deprotected 1-Alkenyl-*o*-carboranes.

Compound	Overall Product % Yield
4	53
7	59
6	40
9	55
10	43

dicarbaundecaborate(1-) ions produced in this study were isolated by HPLC as the tetrabutylammonium salts and characterized by ^{13}C, ^{1}H, and ^{11}B NMR. As a representative example, the corresponding spectra of the *nido*-derivative, $[(C_4H_9)_4N][B_9C_2H_{11}(C_5H_9)]$ (**11**), obtained in the synthesis of 5-*o*-carboranyl-1-pentene are shown in Figures 4, 5 and 6.

In the ^{13}C NMR spectrum of **11** (Figure 4), the signals at δ 58.41, 23.41, 19.12, and 13.10 are due to the tetrabutylammonium ion and the singlet at δ 128 is due to benzene. The remaining resonances are due to the open cage, dicarbadodecahydroundecaborate(-1) ion which is substituted with a 1-pentenyl group at one of the cage carbons. The chemical shifts of the almost fully relaxed signals of the two open cage carbons, at δ ~61 and ~48 in **11**, are shifted considerably upfield from the corresponding signals in **9** (δ 75.4 and 61.2, respectively). In the ^{1}H NMR spectrum of **11** (Figure 5), the broad resonance at δ -2.7 is due to the bridged "extra" proton in the open pentagonal face of the undecaborate(-1) ion.

Finally, in the ^{11}B NMR spectrum (Figure 6) of **11** the following signals were

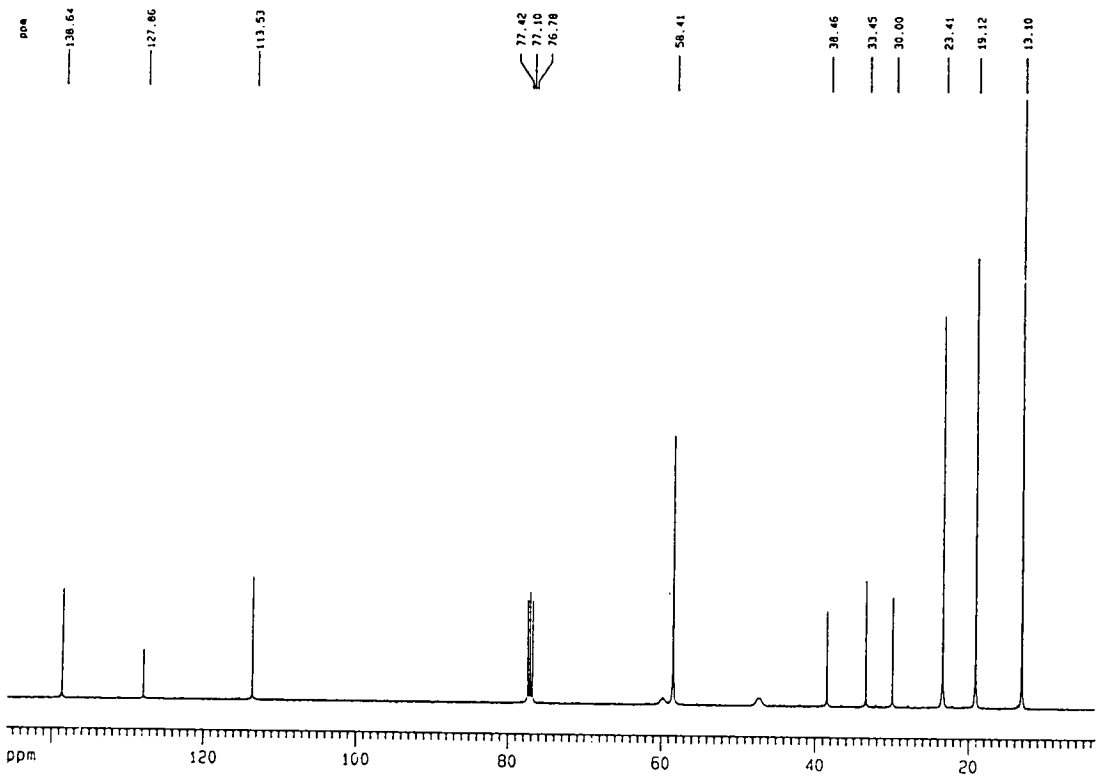


Figure 4. ^{13}C NMR spectrum of the tetrabutylammoniumdodecahydro-*nido*-7,8-dicaundecaborate salt $[(C_4H_9)_4N][B_9C_2H_{11}(C_5H_9)]$ **(11)**

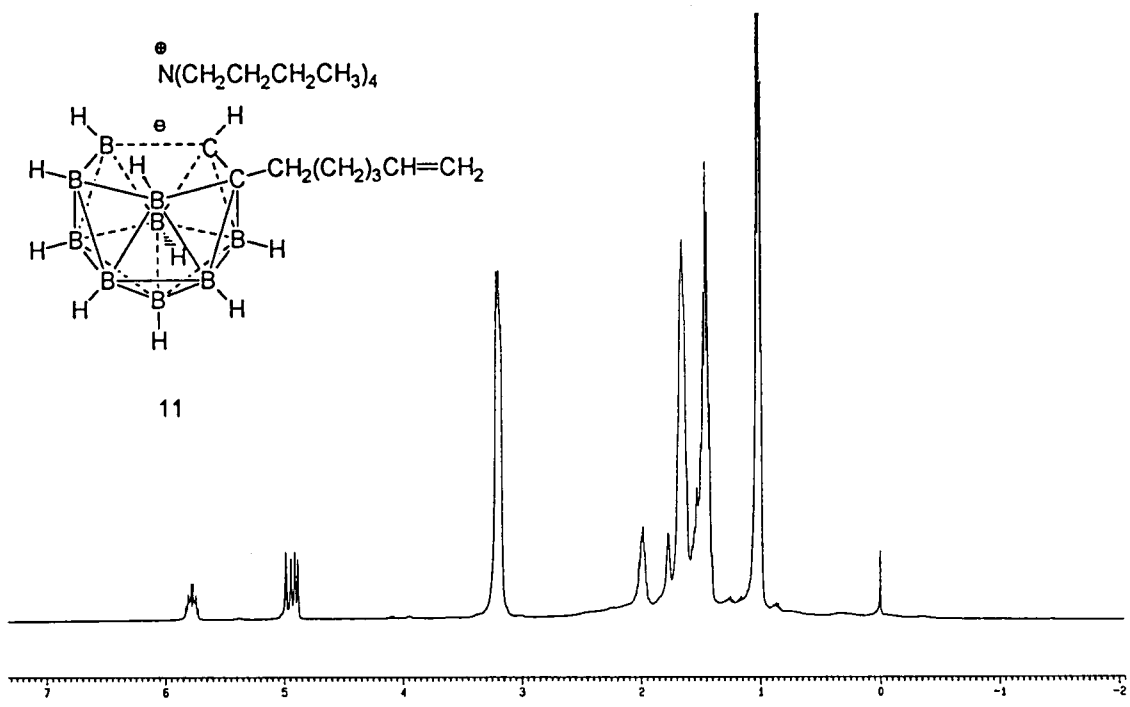


Figure 5. ^{1}H NMR spectrum of the tetrabutylammoniumdodecahydro-*nido*-7,8-dicaundecaborate $[(C_4H_9)_4N][B_9C_2H_{11}(C_5H_9)]$ **(11)**

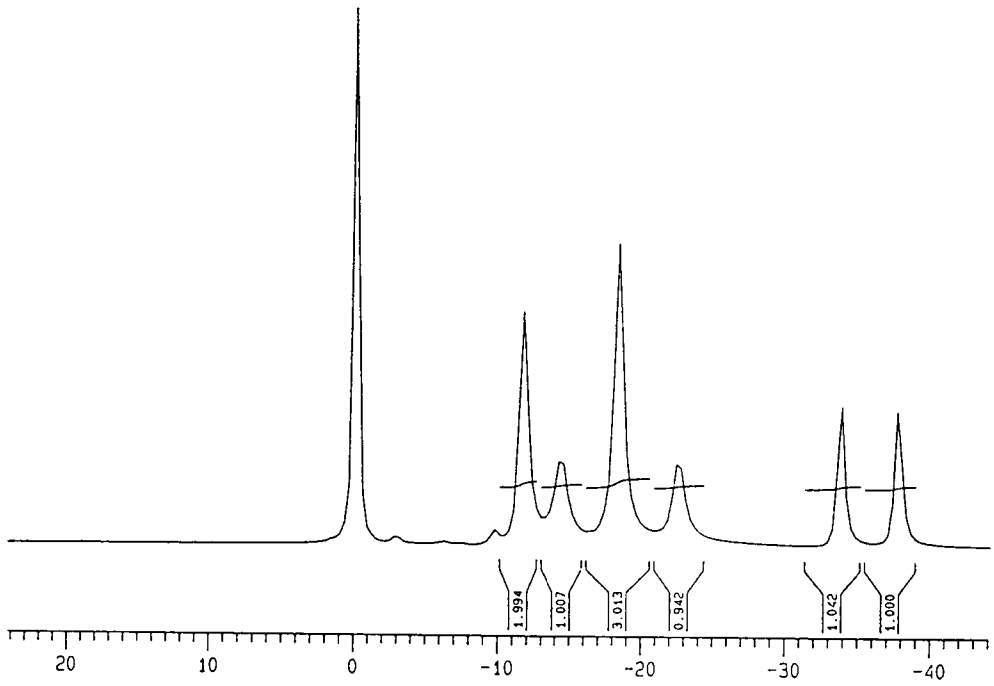


Figure 6. ^{11}B NMR spectrum of the tetrabutylammoniumdodecahydro-*nido*-7,8-dicaundecaborate salt $[(C_4H_9)_4N][B_9C_2H_{11}(C_5H_9)]$ **(11)**

observed (ppm): -11.74 (2B), -14.39 (1B), -18.37 (4B), -22.62 (1B), -33.86 (1B), and -37.76 (1B). The last two signals are assigned to the boron atoms adjacent to the carbon atoms in the open pentagonal face of **11** (133).

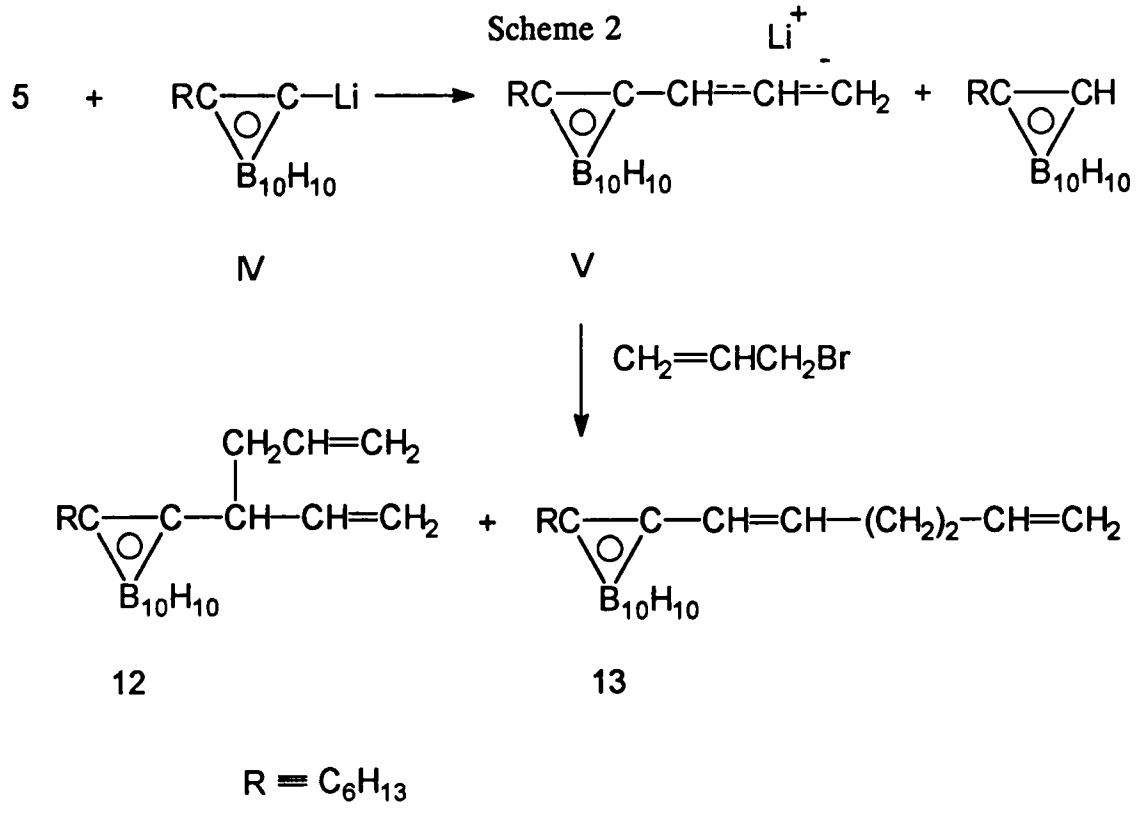
Zakharkin and coworkers (154) reported that 1-allyl-2-alkyl-*o*-carboranes can be readily metallated in the allyl group by *n*-butyllithium in an ether/benzene medium with formation of 1-(lithioallyl)-2-alkyl-*o*-carboranes. Reactions of these intermediates with H_2O resulted in the formation of mixtures of 1-allyl and *trans*-1-propenyl-2-alkyl-*o*-carboranes, the proportion of which varied with the conditions utilized. In the present study, during the synthesis of **5**, the reaction of allyl bromide with a solution of (2-hexyl-*o*-carboran-1-yl)lithium (**IV**) in an ether/benzene mixture at 0 °C followed by a brief reflux (30 min), afforded by GC/MS after work-up: 1-hexyl-*o*-carborane (20%), 1-allyl-2-hexyl-*o*-carborane (62%), and a 8:1 mixture of 3-(2-hexyl-*o*-carboran-1-yl)-1,5-pentadiene (**12**) and 6-(2-hexyl-*o*-carboranyl-1-yl)-1,5-pentadiene (18%) (**13**). This mixture was separated into three fractions by HPLC on an ODC-3 column (10% H_2O-90%EtOH). Examination of these fractions, by ^{13}C and ^{1}H NMR, showed that the first fraction was pure 1-hexyl-*o*-carborane and the second fraction was a 7:1 mixture of 1-allyl-2-hexyl-*o*-carborane (**5**) and *trans*-1-(1-propenyl)-2-hexyl-*o*-carborane (**14**). In the ^{13}C NMR spectra of **5** and **14**, the aliphatic regions containing resonances due to the 2-hexyl group were identical but, in the vinylic region, **5** gave rise to two signals at δ 132.6 and 119.4, whereas **14** contained signals at δ 139.2 and 123.5. Finally, the methyl group in **14** resonated at δ 17.9. GC/MS gave only one peak for both compounds. This behaviour is identical

to what was observed prior to separation, thus excluding the possibility that isomerization occurred during purification. The ^{13}C NMR spectrum of the third fraction revealed 8 signals in the vinylic region corresponding to two isomers containing two double bonds each. Furthermore, both the ^{13}C and ^{1}H NMR data supported the presence of a methine group adjacent to the carborane cage in one of the two isomers. Thus the ^{13}C NMR spectrum contained a CH signal at δ 47.0 , whereas ^{1}H NMR contained a multiplet integrating for one proton at δ 2.48. This is consistent with a compound such as **12**. Finally, the GC/MS spectrum of fraction 3 contained two peaks, each with a molecular ion cluster with a maximum intensity peak at 308 amu and high mass cut-off peak at 311 amu.

The large amount of 1-hexyl-*o*-carborane in the crude products suggests that **5** is metalated not only by *n*-butyllithium, but also by **IV**; the resulting lithioallyl derivative (**V**) reacts with allyl bromide with formation of the two isomeric dienes (**12**) and (**13**). Any unreacted lithioallyl derivative, upon addition of H_2O, would give a mixture of 1-allyl- and 1-propenyl-2-hexyl-*o*-carboranes (Scheme 2). This problem, however, was easily solved by reversing the order of addition. Thus, when (2-hexyl-*o*-carboranyl-1-yl)lithium in ether/benzene was slowly added to a 50% excess of allyl bromide and the resulting mixture was allowed to stir for 24 h at 25 °C, work-up afforded a 95% yield of 1-allyl-2-hexyl-*o*-carborane, the remaining material consisted of starting alkene.

The difficulties encountered in the synthesis of 1-allyl-2-hexyl-*o*-carborane suggested a method by which 1-propenyl-*o*-carborane could be obtained. Thus, when

Scheme 2



1-allyl-*o*-carborane was treated with two equivalents of *n*-BuLi, followed by addition of H_2O, a mixture of 1-allyl- and *trans*-propenyl-*o*-carborane was obtained in 60:40 ratio. This result was unsatisfactory because the separation of these isomers was not straightforward using either column chromatography (SiO_2/hexanes) or HPLC. The complete formation of the thermodynamically more stable *trans*-propenyl-*o*-carborane was achieved upon treatment of 1-allyl-*o*-carborane with two equivalents of potassium *tert*-butoxide in benzene at 40 °C for 3 h. The smooth transformations of **4** into **3** was monitored by GC/MS in which **4**, eluting at 7.42 min, was slowly converted into **3**, eluting at 7.6 min. The mass spectra of both compounds were identical. They contained a molecular ion cluster with maximum intensity peak at 182 amu and high mass cut-off peak at 186 amu. This synthesis, however, afforded a low yield (45%)

of the desired product because degradation of the cage also occurred to afford the potassium salt of the propenyl substituted 1,2-dicarbaundecaborate(-1) ion. **3** was purified by HPLC to afford a white solid of mp 78-79 °C. It was further characterized by high resolution mass spectrometry. The H/H COSY spectrum of **3** is shown in Figure 7. In the ^{1}H NMR spectrun of 1-propenyl-*o*-carborane the *trans* arrangement at the double bond was inferred from the J value of 15.2 Hz associated with the vinyl protons of the double bond at δ 6.07 and 5.65. The resonance at δ 6.07 was also coupled to the methyl group, J= 6.7 Hz, whereas, the resonance at δ 5.65 revealed a coupling constant of 1.8 Hz, establishing their relative positions. The signal at δ 3.58 is due to the hydrogen on the cage carbon.

The synthesis of 1-isopropenyl-*o*-carborane (**2**) was accomplished by decarboxylation, under brief reflux, of an aqueous solution of the potassium salt of 1-isopropenyl-*o*-carboranecarboxylic acid. After work-up, **2** was further purified by HPLC. The ^{1}H NMR spectrum of **2** showed two singlets at δ 5.24 and 5.12 due to the vinyl protons, a singlet at δ 3.76 due to the acidic C-H proton of the cage and a singlet at δ 1.89 due to the methyl group α to the cage. The C/H COSY spectrum of **2** is shown in Figure 8.

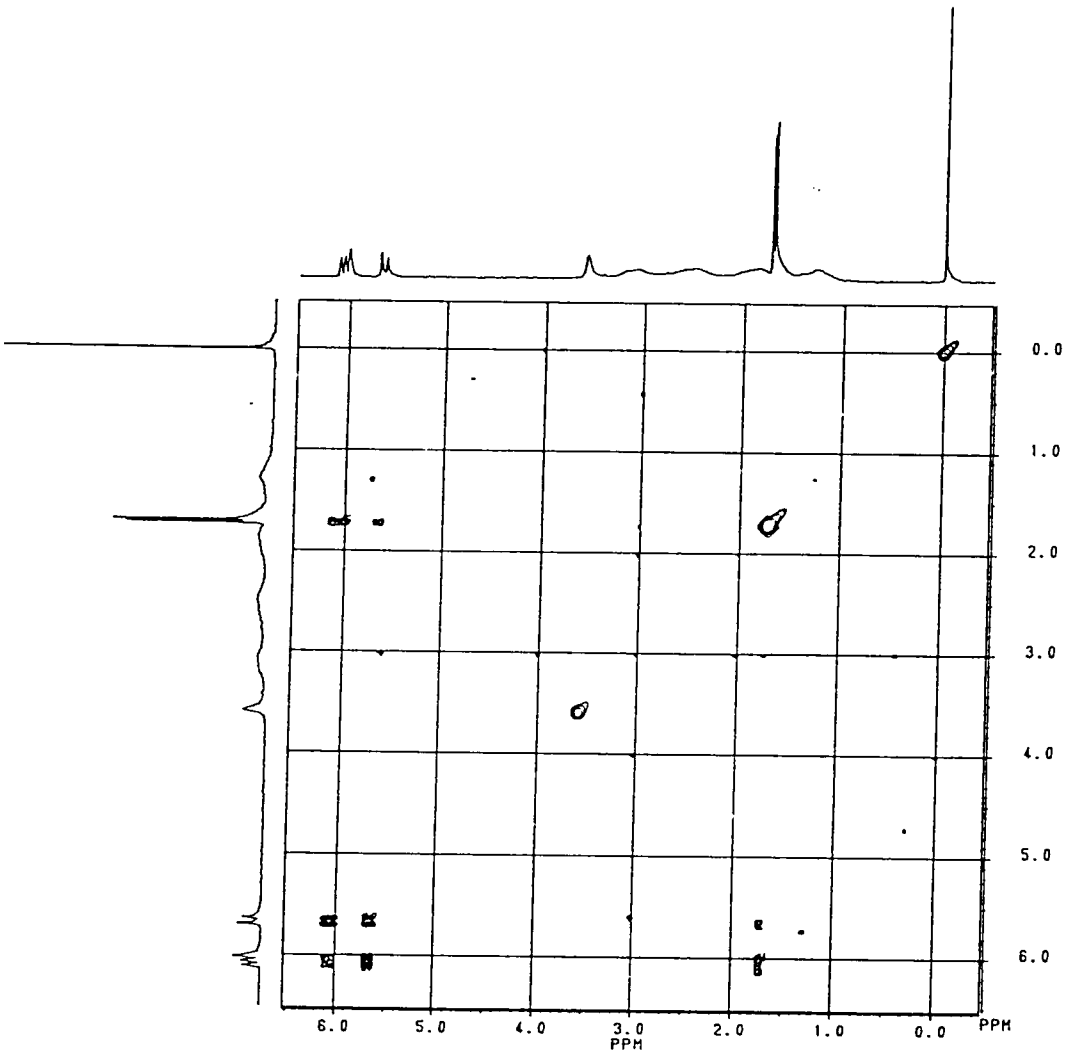


Figure 7. H/H COSY NMR spectrum of 1-*trans*-propenyl-*o*-carborane (**3**).

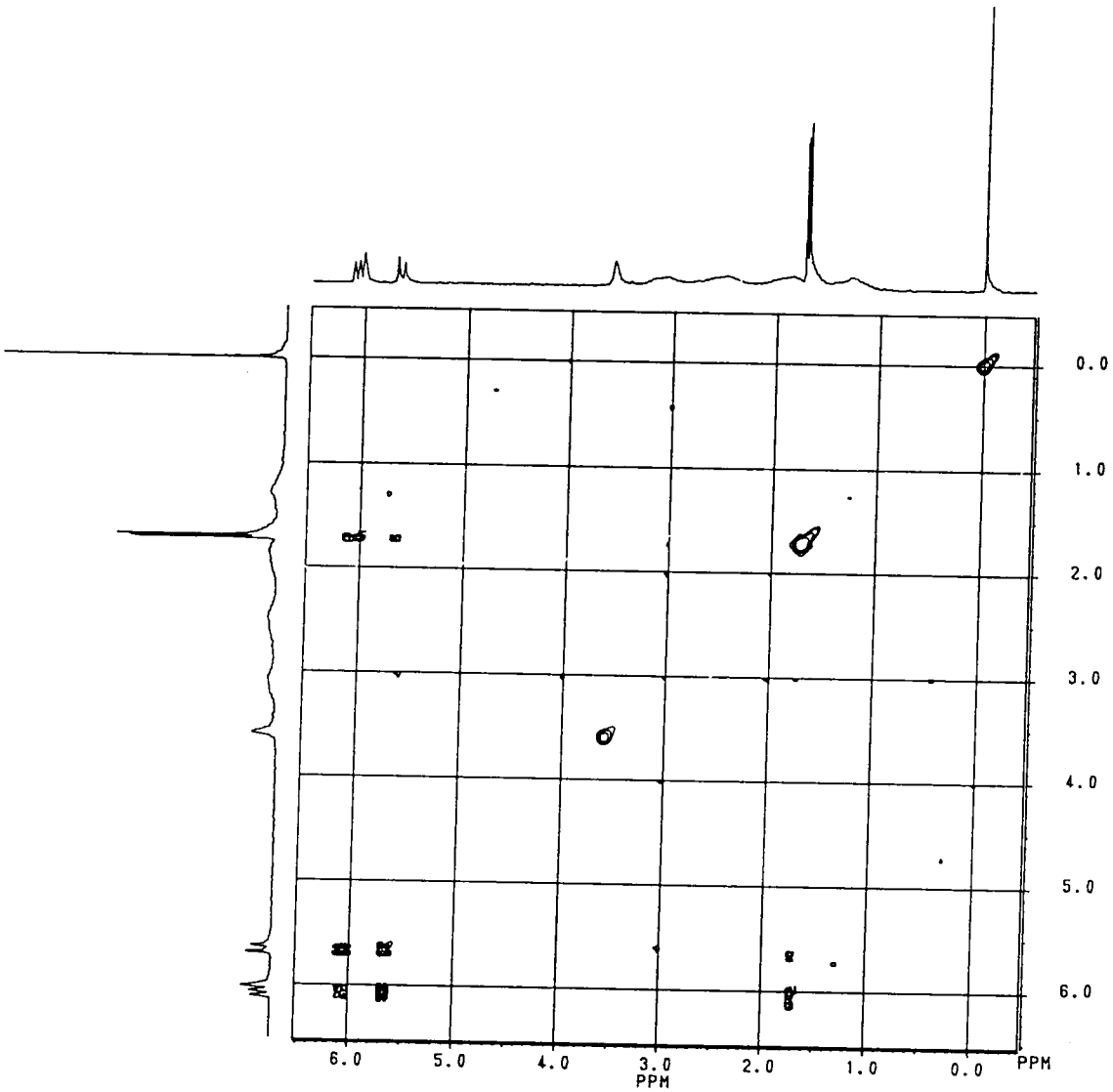


Figure 8. C/H COSY NMR spectrum of 1-isopropenyl-*o*-carborane (**2**).

2.3 *Experimental Section*

The reaction flask and other glassware were stored overnight in an oven at 150°C and assembled in a stream of dry nitrogen gas. Syringes were assembled and fitted with needles while hot and cooled in a stream of dry nitrogen gas. The handling of air sensitive materials was carried out in a dry box or in a glove bag under argon or nitrogen.

Proton (^{1}H NMR) and carbon (^{13}C NMR) spectra were obtained on a Bruker AMX 400 spectrometer at 400.13 and 100.62 MHz, respectively. Boron (^{11}B NMR) spectra were obtained at 128.38 MHz on the Bruker AMX 400 spectrometer. Chemical shifts for ^{1}H NMR and ^{13}C NMR spectra were referenced to $SiMe_4$ (0.00 ppm) and measured with respect to residual protons in the deuterated solvent. Chemical shift values for ^{11}B spectra were referenced relative to $BF_3{\cdot}OEt_2$ (0.00 ppm). Coupling constants (J) are given in Hertz. Resonances observed upfield of the references were assigned negative chemical shift values in all cases. Mass spectra were recorded on GC/MS (Hewlett-Packard 5890 gas chromatograph and 5970 series mass selective detector equipped with a crossbonded 100% dimethylpolysiloxane column.) Melting points were determined on a Thomas-Hoover capillary melting point apparatus. The melting points were uncorrected.

The gas chromatographic analyses were performed on either a Varian 3700 Model or a Hewlett-Packard 5750 model chromatograph. The following columns were used: 5% SE-30 on Chromosorb W, 10 ft x 0.25 in. and 10% SE-30 on Chromosorb W, 10 ft x 0.25 in.; and 10% Carbowax 20M on Chromosorb W, 10 ft

x 0.25 in. Products were isolated by HPLC on a Varian Model 5000 HPLC which had a programmable gradient elution capability on an ODC-3 column.

The *o*-carborane, vinyl-*o*-carborane, methyl-*o*-carborane, and hexyl-*o*-carborane were purchased from Dexsil Corp. The remaining reagents were obtained from sources indicated in Table 11.

1-Vinyl-o-carborane (1). The 1-Vinyl-*o*-carborane used in this work was obtained from Dexsil corp., and purified by vacuum sublimation. Purity was checked by mass spectrometry, ^{1}H NMR, ^{13}C NMR, and ^{11}B NMR. The purified material was a waxy solid at room temperature with a sharp melting point at 79 °C: ^{1}H NMR (THF-d_8) δ 6.09 (dd, 1H, J = 16.92, 10.56 Hz), 5.60 (d, 1H, J = 16.92 Hz), 5.36 (d, 1H, J = 10.56 Hz), 4.57 (s, 1H); ^{13}C NMR (THF-d_8) δ 133.2, 122.4, 74.8, 61.60; ^{11}B NMR (THF-d_8) δ -2.28 (d, 1B), -4.86 (d, 1B), -9.05 (d, 2B) -11.21 (d, 4B), -12.78 (d, 2B).

1-Isopropenyl-*o*-carborane (2). The potassium salt of 1-isopropenyl-*o*-carboranecarboxylic acid (11.3 mmol, 3.02 g) was refluxed with H_2O (50 mL) for 15 min. After cooling to 25° C, the mixture was transferred to a separatory funnel and diluted with diethyl ether (50 mL). The layers were separated and the aqueous layer was extracted with additional Et_2O (2 x 20 mL). The combined extracts were then dried over anhydrous $MgSO_4$ and concentrated *in vacuo*. HPLC separation on an ODC-3 column [H_2O (20%):MeOH (80%)] afforded a 62% yield (7.13 mmol, 1.33 g) of a white fine solid: mp 43-45° C; ^{1}H NMR ($CDCl_3$) δ 5.24 (s, 1H), 5.12 (s, 1H), 3.77 (s, 1H), 1.89 (s, 3H); ^{13}C NMR ($CDCl_3$) δ 137.9, 118.5, 77.1, 59.5, 23.1; ^{11}B NMR ($CDCl_3$) δ -3.06 (d, 1B) -4.93 (d, 1B), -9.40 (d, 2B), -11.51 (d, 2B), -12.06 (d,

Table 11. Source of Commercial Reagents.

Reagent	Source
Dibromobenzene	F
Boron Trifluoride-Diethyl Etherate	A[b]
Calcium Hydride	Al[c]
Cyclohexene	E[d]
Ethanol	F
Hydrochloric Acid	AC[e]
Hydrogen Peroxide	F
Lithium Aluminum Hydride	Al
Methanol	F
Potassium Hydroxide	F
Sodium Chloride	F
Sodium Hydroxide	F
n-Butanol	F
Tetrahydrofuran	A
n-Tetradecane	A
n-Hexadecane	A
Potassium *t*-Butoxide	A
n-Butyllithium	A
Allyl bromide	A
4-Bromo-1-butene	A
5-Bromo-1-butene	A
8-Bromo-1-octene	A
4-Bromo-2-butene	A
N,O-(Trimethylsilyl)trifluoroacetamide	P
Benzophenone	A
Molecular Sieves 4Å	B

a) F Fisher Scientific Company
b) A Aldrich Chemical Company
c) Al Alfa Chemical Products
d) E Eastman Kodak
e) AC Allied Chemical Company
f) B J.T. Baker Chemical Company
g) P Pierce Chemical Company

2B), -13.58 (d, 2B).

1-(1-Propenyl)-*o*-carborane (3). A solution of 1-allyl-*o*-carborane (15.19 mmol, 2.832 g), in benzene (20 mL) and potassium *tert*-butoxide (24.3 mmol, 2.73 g) was heated for 3 h at 40-45° C. The mixture was neutralized and washed with water (30 mL). The layers were separated and the aqueous layer was extracted with Et_2O (3 x 30 mL). The combined extracts were dried over anhydrous $MgSO_4$ and concentrated *in vacuo* to give **3** as a fine white solid. This was further purified by HPLC on an ODC-3 column [H_2O (15%): MeOH (85%)] to afford a 45% yield (6.84 mmol, 1.27 g) of a white solid: mp 78-79° C; ^1H NMR ($CDCl_3$) δ 6.07 (1H, dd, J = 15.3, 6.7), 5.66 (1H, dd, J = 15.3, 1.8), 1.71 (3H, dd, J = 6.7, 1.8); ^{13}C NMR ($CDCl_3$) δ 135.3, 125.4, 74.2, 60.9, 17.6; ^{11}B NMR ($CDCl_3$) δ -2.29 (d, 1B), -5.62 (d,1B), -9.63 (d,2B), -11.28 (d,2B), -12.01 (d, 2B), -13.20 (d, 2B). The [1,2-$B_9C_2H_{11}(C_3H_5)$][K] salt was also isolated. Only the high field signals in the ^{11}B spectrum could be unambiguously assigned. ^{11}B NMR ($CDCl_3$) δ -23.32 (d, 1B), -33.11 (d, 1B), -36.75 (d, 1B).

1-Silyl-*o*-carborane. To a solution of 1,2-dicarbo-*closo*-dodecaborane (99.8 mmol, 14.4 g), in a dry benzene/diethyl ether (2:1) mixture (85 mL) at 0° C, was added *n*-BuLi in hexane (105 mmol, 42.0 mL, of a 2.5 *M* solution) dropwise with stirring. The mixture was allowed to stir for 30 min while being warmed to ambient temperature. The solution was cooled to 0° C and *tert*-butyldimethysilyl chloride (110 mmol, 16.5 g) in a benzene/diethyl ether (2:1) mixture (25 mL) was added rapidly dropwise. The solution was refluxed overnight, quenched with water (42 mL), transferred to a separatory funnel and diluted with diethyl ether (85 mL). The layers were separated

and the aqueous layer was extracted with additional Et_2O (2 x 300 mL). The combined extracts were then dried over anhydrous $MgSO_4$ and concentrated *in vacuo*. Heating the mixture to 80 °C (0.001 mm Hg) removed unreacted 1,2-dicarba-*closo*-dodecaborane by sublimation. The product was distilled at 120 °C to yield 90% of the desired product (89.8 mmol, 23.2 g): mp 54-56° C; ^1H NMR ($CDCl_3$) δ 3.28(s, 1H), 1.05(s,9H), 0.30 (s,6H); ^{11}B NMR ($CDCl_3$) δ 0.05(d,1B), -2.02 (d,1B), -7.25 (d,2B), -10.97(d,2B), -12.52 (d,2B), -13.49 (d,2B).

1-Allyl-2-silyl-*o*-carborane. To a solution of silyl-*o*-carborane (17.5 mmol, 4.52 g), in a dry benzene/diethyl ether mixture (50 mL) at 0 °C, was added *n*-BuLi in hexane (7.80 mmol, 7.11 mL of a 2.50 *M* solution) dropwise with stirring. The mixture was allowed to stir for 30 min while being warmed to ambient temperature, cooled to 0 °C, and allyl bromide (17.9 mmol, 1.55 mL) was added dropwise with stirring. After refluxing overnight, the solution was quenched with water (30 mL), transferred to a separatory funnel, and diluted with diethyl ether (60 mL). The layers were separated and the aqueous layer was extracted with Et_2O (2 x 50 mL). The combined organic extracts were then dried over anhydrous $MgSO_4$ and concentrated *in vacuo* to give a 73 % yield (12.8 mmol, 3.82 g).

1-Homoallyl-2-silyl-*o*-carborane. To silyl-*o*-carborane (17.8 mmol, 4.59 g), in a dry benzene/diethyl ether mixture (50 mL) at 0 °C, was added *n*-BuLi in hexane (18.8 mmol, 7.51 mL of a 2.50 *M* solution) dropwise with stirring. The mixture was allowed to stir for 30 min while warming to room temperature. The solution was then cooled to 0 °C and 4-bromo-1-butene (19.4 mmol, 2.00 mL) was added dropwise

with stirring. After refluxing overnight and the usual work-up, the reaction afforded 75% (13.4 mmol, 4.18 g) of 1-homoallyl-2-silyl-*o*-carborane.

1-Crotyl-2-silyl-*o*-carborane. A solution of silyl-*o*-carborane (19.8 mmol, 5.11 g), in a dry benzene/diethyl ether mixture (50 mL) at 0 °C, was treated with *n*-BuLi in hexane (20.3 mmol, 8.10 mL of a 2.50 *M* solution) dropwise with stirring. The mixture was stirred for 30 min while it was slowly brought to ambient temperature. The solution was cooled to 0 °C and 1-bromo-2-butene (85:15 *trans/cis* mixture) (20.4 mmol, 2.15 mL) was added dropwise with stirring. After refluxing overnight, the usual work-up afforded a 77% yield (15.2 mmol, 4.75 g) of a *cis/trans* mixture of 1-crotyl-2-silyl-*o*-carborane.

1-(4-Pentenyl)-2-silyl-*o*-carborane. To a solution of silyl-*o*-carborane (23.6 mmol, 6.10 g), in a dry benzene/diethyl ether mixture (60 mL) at 0° C, was added *n*-BuLi in hexane (25.0 mmol, 10.0 mL, of a 2.50 *M* solution) dropwise with stirring. The mixture was allowed to stir for 30 min while being warmed to 25 °C. The solution was cooled to 0 °C and 5-bromo-1-pentene (26.7 mmol, 3.10 mL) was added dropwise with stirring. After refluxing overnight and the usual work-up, the reaction afforded a 71% yield (16.7 mmol, 5.44 g) of the desired product.

1-(7-Octenyl-2-silyl-*o*-carborane. To a silyl-*o*-carborane (28.1 mmol, 7.25 g), in a dry benzene/diethyl ether mixture (80 mL) was added *n*-BuLi in hexane (29.5 mmol, 11.8 mL of a 2.50 *M* solution) dropwise with stirring. The mixture was allowed to stir for 30 min while warming to ambient temperature. The solution was then cooled to 0 °C and 8-bromo-1-octene (30.9 mmol, 5.18 mL) was added dropwise with stirring.

After refluxing overnight, work-up afforded a 63% yield (17.6 mmol, 6.50 g) of the desired olefin.

1-Allyl-*o*-carborane (4). A solution of 1-allyl-2-silyl-*o*-carborane (12.0 mmol, 3.58 g) in dry THF (35 mL) was cooled to -76 °C and tetrabutylammonium fluoride in THF (13.2 mmol, 13.2 mL of a 1.00 *M* solution) was added dropwise with stirring. The mixture was allowed to stir for 30 min while warming to room temperature and water (15 mL) was added. The solution was diluted with diethyl ether (20 mL) and transferred to a separatory funnel. The layers were separated and the aqueous layer was extracted into Et_2O (2 x 25 mL). The combined extracts were dried over anhydrous $MgSO_4$ and concentrated *in vacuo* to give **4** as a viscous liquid in 72% yield (8.59 mmol, 1.58 g). Spectroscopic data were in agreement with the literature (153). ^1H NMR (acetone-d_6) δ 5.69 (1H, ddt, J=18.4, 10.0, 7.2 Hz), 5.20 (1H, d, J=10.0 Hz), 5.13 (1H, dt, J=16.8, 1.2Hz), 2.951 (2H, d, J=7.2 Hz); ^{13}C NMR ($CDCl_3$) δ 131.2. 120.1, 73.7, 59.6, 41.8; ^{11}B NMR (acetone) δ -2.27 (d, 1B), -5.44 (d, 1B), -8.95 (d, 2B), -10.82 (d, 2B), -11.73 (d, 2B), -12.37 (d, 2B). The purification process mentioned above (HPLC) also afforded the $[1,2\text{-}B_9C_2H_{11}(C_3H_5)][(C_4H_9)_4N]$ salt: ^{11}B NMR ($CDCl_3$) δ -11.18 (2B,d), -14.08 (1B,d), -18.57 (3B,d), -23.19 (1B,d), -33.43 (1B,d), -36.62 (1B,d).

1-Homoallyl-*o*-carborane (7). A solution of 1-homoallyl-2-silyl-*o*-carborane (12.8 mmol, 3.98 g), in dry THF (35 mL) was cooled to -76 °C and tetrabutylammonium fluoride in THF (14.2 mmol, 14.2 mL of a 1.00 *M* solution) was added dropwise with stirring. The mixture was allowed to stir for 30 min while warming to room

temperature and then water (20 mL) was added. The solution was diluted with diethyl ether (20 mL) and transferred to a separatory funnel. The layers were separated and the aqueous layer was extracted with Et_2O (2 x 30 mL). The combined extracts were dried over anhydrous $MgSO_4$ and concentrated *in vacuo* to give an oily product. HPLC purification on an ODC-3 column (80:20-MeOH:H_2O) afforded 53% yield (7.22 mmol, 1.43 g) of the desired alkene: mp 45-46 °C; ^{1}H NMR ($CDCl_3$) δ 5.75 (m, 1H), 5.04 (m, 2H), 4.57 (s, 1H), 2.42 (m, 2H), 2.25 (m, 2H); ^{13}C NMR (acetone-d_6) δ 136.4, 116.5, 76.3, 63.1, 37.3, 33.7; ^{11}B NMR (acetone) δ -2.40 (d,1B), -5.50 (d,1B), -9.08 (d,2B), -10.96 (d,4B), -12.51 (d,2B).

1-Crotyl-*o*-carborane (6). A solution of 1-crotyl-2-silyl-*o*-carborane (13.8 mmol, 4.32g) in dry THF (35 mL) was cooled to -76 °C and tetrabutylammonium fluoride in THF (15.0 mmol, 15.0 mL of a 1.00 *M* solution) was added dropwise with stirring. The mixture was allowed to stir for 30 min while warming to room temperature, and water (20 mL) was added. The solution was diluted with diethyl ether (20 mL) and transferred to a separatory funnel. The layers were separated and the aqueous layer was extracted with Et_2O (2 x 30 mL). The combined extracts were dried over anhydrous $MgSO_4$ and concentrated *in vacuo* to give a viscous liquid of **6** as a *cis/trans* mixture in 76% yield (10.5 mmol, 2.08 g). <u>*trans* isomer</u>: ^{1}H NMR (C_6D_6) δ 5.55 (m, 1H), 5.33 (m, 1H), 3.56 (s, 1H), 2.93 (d, 2H, J=Hz), 1.71 (d, 3H, J=8 Hz); ^{13}C NMR (C_6D_6): 131.9, 124.2, 74.9, 60.07, 40.70, 17.70. <u>*cis* isomer</u>: ^{1}H NMR (C_6D_6) δ 5.73 (m, 1H), 5.35 (m, 1H), 3.56 (s, 1H), 2.99 (d,2H, J=8 Hz), 1.62 (d, 3H, J=8 Hz); ^{13}C NMR (C_6D_6) δ 129.8, 123.2, 74.8, 60.3, 34.4; ^{11}B NMR (C_6D_6); <u>*cis/trans*</u>

mixture δ -2.83 (d, 1B), -6.13 (d, 1B), -9.49 9d, 2B), -11.28 (d, 2B), -13.25 (d, 4B). The purification process (HPLC) also afforded the $[1,2\text{-}B_9C_2H_{11}(C_4H_9)][(C_4H_9)_4N]$ salt: ^{11}B NMR ($CDCl_3$) δ -11.31 (2B, d), -14.21 (1B, d), -18.24 (3B, d), -22.49 (1B, d), -33.73 (1B, dd, J = 123.1 and 41.2 Hz), -37.47 (1B, d).

1-(4-Pentenyl)-*o*-carborane (9). A solution of 1-(4-pentenyl)-2-silyl-*o*-carborane (16.4 mmol, 5.36 g) in dry THF (50 mL) was cooled to -76 °C and tetrabutylammonium fluoride in THF (17.0 mmol, 17.0 mL of a 1.00 *M* solution) was added dropwise with stirring. Work-up in the usual way and purification by HPLC afforded **9** as a viscous liquid in 78% yield (12.8 mmol, 2.71 g): ^{1}H NMR (C_6D_6) δ 5.51 (m, 1H), 4.88 (m, 2H), 3.06 (s, 1H), 1.80 (m, 2H), 1.72 (m, 2H), 1.23 (m,2H); ^{13}C NMR ($CDCl_3$) δ 136.7, 116.1, 75.4, 61.2, 37.3, 32.7, 28.3; ^{11}B NMR (acetone) δ -2.02 (d, 1B), -5.24 (d, 1B), -8.75 (d, 2B), -10.7 (d, 4B), -12.1 (d, 2B). The purification process (HPLC) also afforded the $[1,2\text{-}B_9C_2H_{11}(C_5H_9)][(C_4H_9)_4N]$ salt (15%): ^{11}B NMR ($CDCl_3$) δ -11.74 (2B, d), -14.39 (1B, d), -18.39 (2B, d), -22.62(1B, d), -33.88 (1B, d), -37,76 (1B, d); ^{13}C NMR ($CDCl_3$) δ 136.6, 113.5, 60.0, 47.5, 38.4, 33.4, 30.00; (C_4H_7)N: 58.41, 23.41, 19.12, 13.10; ^{1}H NMR ($CDCl_3$) δ 5.767 (1H, m), 4.926 (2H, m), 1.993 (2H, m), 1.772 (2H, m), 1.523 (2H, m); $(C_4H_7)_4$N: 3.193 (2H,m), 1.787 (2H,m), 1.528 (2H,m), 1.012 (3H, t, J = 7.04 Hz).

1-(7-Octenyl)-*o*-carborane (10). A solution of 1-(7-octenyl)-2-silyl-*o*-carborane (13.9 mmol, 5.13 g), in dry THF (40 mL) was cooled to -76 °C and tetrabutylammonium fluoride in THF (14.8 mmol, 14.8 mL of a 1.00 *M* solution) was added dropwise with stirring. Work-up in the usual fashion afforded **10** as a viscous clear liquid in 67%

yield (9.28 mmol, 2.36 g): ^{1}H NMR (C_6D_6) δ 5.73 (m, 1H), 4.97 (m, 2H), 2.70 (s, 1H), 1.97 (m, 2H), 1.68 (m, 2H), 1.23 (m,2H), 1.07 (m,6H), 0.91 (m,2H); ^{13}C NMR ($CDCl_3$) δ 138.7, 114.5, 75.6, 61.1, 38.1, 33.6, 29.2, 28.8, 28.6, 28.5; ^{11}B NMR (CD_3Cl) δ -2.78 (d, 1B), -6.25 (d, 1B), -9.66 (d, 2B), -11.72 (d, 4B), -12.43 (d, 2B), -13.39 (d, 2B). The purification process (HPLC) also afforded the [1,2-$B_9C_2H_{11}(C_8H_{15})$][$(C_4H_9)_4N$] salt: ^{11}B NMR ($CDCl_3$) δ -11.61 (2B, d), -14.16 (1B, d), -18.29 (3B, d), -22.54 (1B, d), -33,74 (1B, d), -37.70 (1B, d); ^{13}C NMR ($CDCl_3$) δ 138.75, 113.67, ~60, ~49, 39.11, 33.38, 30.83, 29.29, 28.70, 28.49; $(C_4H_9)_4N$: 58.46, 23.53, 19.24, 13.22.

1-Allyl-*o*-carborane (4). To a stirred solution of *o*-carborane (17.5 mmol, 2.52 g) in ether (10.5 mL) at 0 °C, under an argon flow, was added, dropwise, a solution of *n*-butyllithium in pentanes (18.4 mmol, 14.7 mL of a 1.25 *M* solution). The mixture was warmed to room temperature, stirred for 1 h, and then cooled again to 0 °C. A solution of allyl bromide (18.5 mmol, 1.60 mL) in ether (18 mL) was then added dropwise to the reaction mixture. The resulting mixture was warmed to room temperature, stirred for 2 h, and then heated at reflux for 3 h. Upon cooling, the reaction mixture was treated with water (30 mL). The ether layer was separated, washed with water until pH=7, dried over $MgSO_4$, and then the solvent evaporated under reduced pressure using a rotatory evaporator to give 3.1 g of an orange liquid. Analysis of the crude product by GC/MS indicated the following distribution of products: *o*-carborane (19%); 1-allyl-*o*-carborane (62%); and 1,2-bis-(allyl)-*o*-carborane (19%). The unreacted *o*-carborane was removed by sublimation at 100°

C (0.1 mm). The desired 1-allyl-*o*-carborane was isolated by fractional distillation at 75-85 °C (0.07-0.1 mm) in 45% yield.

1-Allyl-2-hexyl-*o*-carborane (5). 1-Hexyl-*o*-carborane (12.7 mmol, 2.89 g), was dissolved in benzene (30 mL). The solution was cooled to 0 °C and *n*-butyllithium in hexane (13.0 mmol, 8.10 mL of a 1.60 *M* solution) added slowly. After the addition was complete, the mixture was allowed to stir for 2 h and then it was refluxed for an additional 30 min. A white precipitate, due to lithium bromide, formed during the reaction. A solution of allyl bromide (13.6 mmol, 1.18 mL) in ether (10 mL) was added slowly at 0 °C and the resulting mixture was refluxed for 1 h and then cooled. The reaction mixture was quenched with sufficient dilute hydrochloric acid (10%) to dissolve the lithium bromide formed. The organic layer was separated and the aqueous layer extracted with ether (3 × 20 mL). The combined organic extracts were concentrated *in vacuo* to afford a light green viscous liquid. HPLC separation afforded three fractions. The first fraction (20%) contained unreacted starting material. The second fraction (62%) contained a mixture of 1-allyl-2-hexyl-*o*-carborane and 1-propenyl-2-hexyl-*o*-carborane, and the third fraction (18%) consisted of a mixture of two compounds each containing two double bonds per molecule. The aliphatic region of the ^{13}C NMR spectrum overlapped. The vinyl region of the ^{13}C NMR spectrum ($CDCl_3$) revealed a major isomer at δ 143.4, 136.8, 122.9, 115.8 and a minor isomer at δ 137.9, 135.0, 118.2, 117.3.

The synthesis of 2-hexyl-*o*-carboran-1-yllithium (**IV**) (8.25 mmol, 1.88 g) was

achieved as described above. This intermediate, however, was transferred via a double ended needle to a solution of allyl bromide (12.7 mmol, 1.10 g) in tetrahydrofuran (20 mL) which was maintained at 0 °C. A deep orange color resulted upon mixing the two solutions. The reaction flask was allowed to stir overnight at 25 °C. Work-up as described above, and purification of the desired product via HPLC, afforded a 80% yield (6.60 mmol, 1.76 g) of a clear viscous liquid: ^{1}H NMR ($CDCl_3$) δ 5.7 (m, 1H), 5.17 (d, 1H, J=10.4 Hz), 5.09 (dt, 1H, J=16.8, 1.2 Hz), 2.93 (d, 2H, J=7.2 Hz), 2.17 (m, 2d), 1.51 (m, 2H), 1.28 (s, 6H), 0.89 (t, 3H, J=7.2 Hz); ^{13}C NMR ($CDCl_3$) δ 132.5, 119.4, 79.6, 78.1, 39.3, 35.0, 31.3, 29.7, 28.9, 22.5, 14.0; ^{11}B NMR ($CDCl_3$) δ -7.10 (d, 2B), -12.82 (d, 8B).

1-Homoallyl-2-methyl-*o*-carborane (8). To a solution of methyl-*o*-carborane (9.49 mmol, 1.50 g) in ethyl ether (10 mL) was added, at -2 °C, the stoichiometric amount of *n*-BuLi in hexanes (9.5 mmol, 3.8 mL of a 2.50 *M* solution) at a fairly rapid rate while keeping the temperature between -2 to 0 °C. After the addition, the temperature was allowed to rise to 10 °C, maintained there for 15 min, and then allowed to reach 25 °C for 5 h. The temperature was again lowered to 0 °C and an equimolar (plus 7%) quantity of 4-bromo-1-butene (10.2 mmol, 1.05 mL), dissolved in an equal volume of ether was added dropwise. After the addition was complete, the reaction mixture was allowed to warm to 25 °C. The solution was refluxed overnight, quenched with water (25 mL) and transferred to a separatory funnel where it was diluted with diethyl ether (15 mL). The layers were separated and the aqueous layer was extracted with ether (2 x 20 mL). The combined extracts were

dried over anhydrous $MgSO_4$ and concentrated *in vacuo*. Sublimation at 90 °C (1 x 10^{-3} mm) removed unreacted methyl-*o*-carborane. The remaining product was purified by HPLC to afford 57% (5.41 mmol, 1.15 g) of pure alkene: mp 40-42 °C; ^{1}H NMR ($CDCl_3$) δ 5.58 (m, 1H), 4.92 (m, 2H), 2.14 (m, 4H), 1.86 (s, 3H); ^{13}C NMR ($CDCl_3$) δ 135.6, 116.7, 77.6, 74.8, 34.7, 33.5, 23.2; ^{11}B NMR ($CDCl_3$) δ -4.25 (d, 1B), -6.25 (d, 1B), -9.35 (d, 2B), -10.2 (d, 2B), -12.1 (d, 4B).

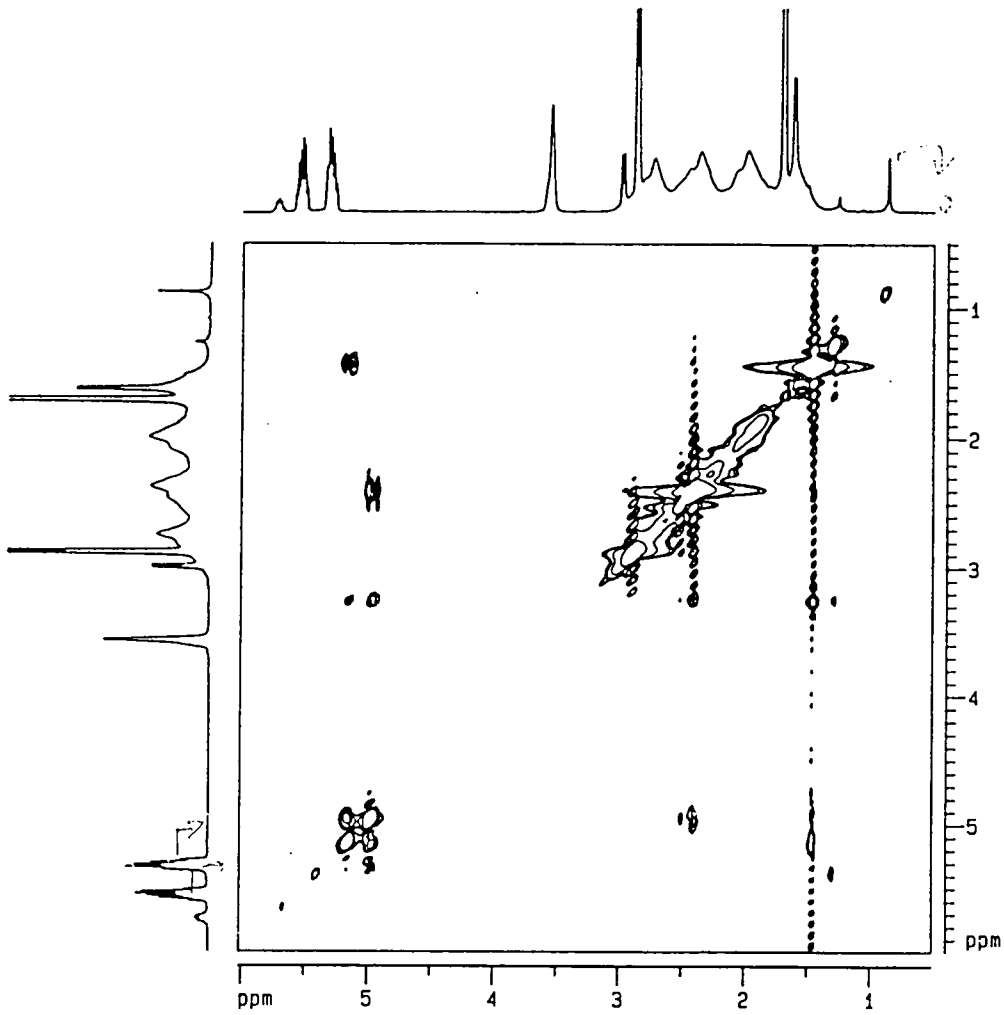


Figure 10. H/H COSY NMR spectrum of 1-crotyl-*o*-carborane (**6**).

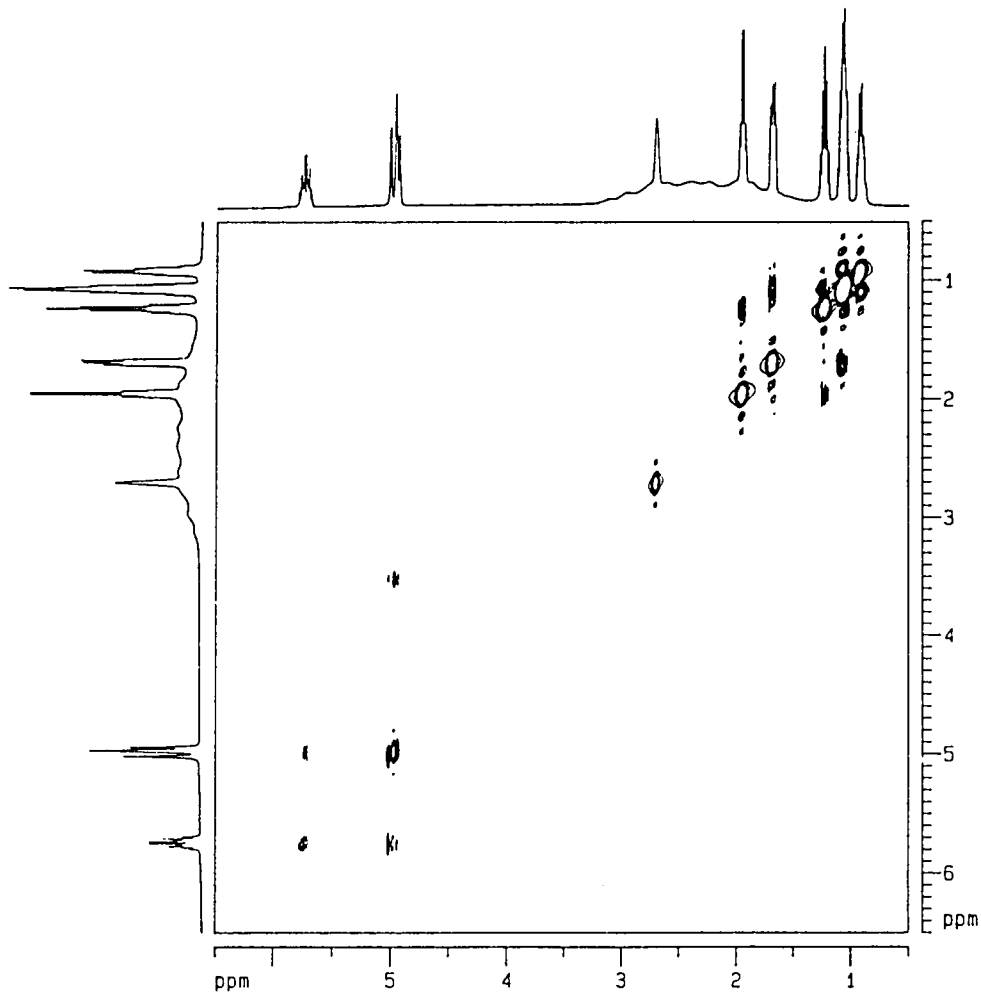


Figure 12. H/H COSY NMR spectrum of 1-(7-octenyl)-*o*-carborane (**10**).

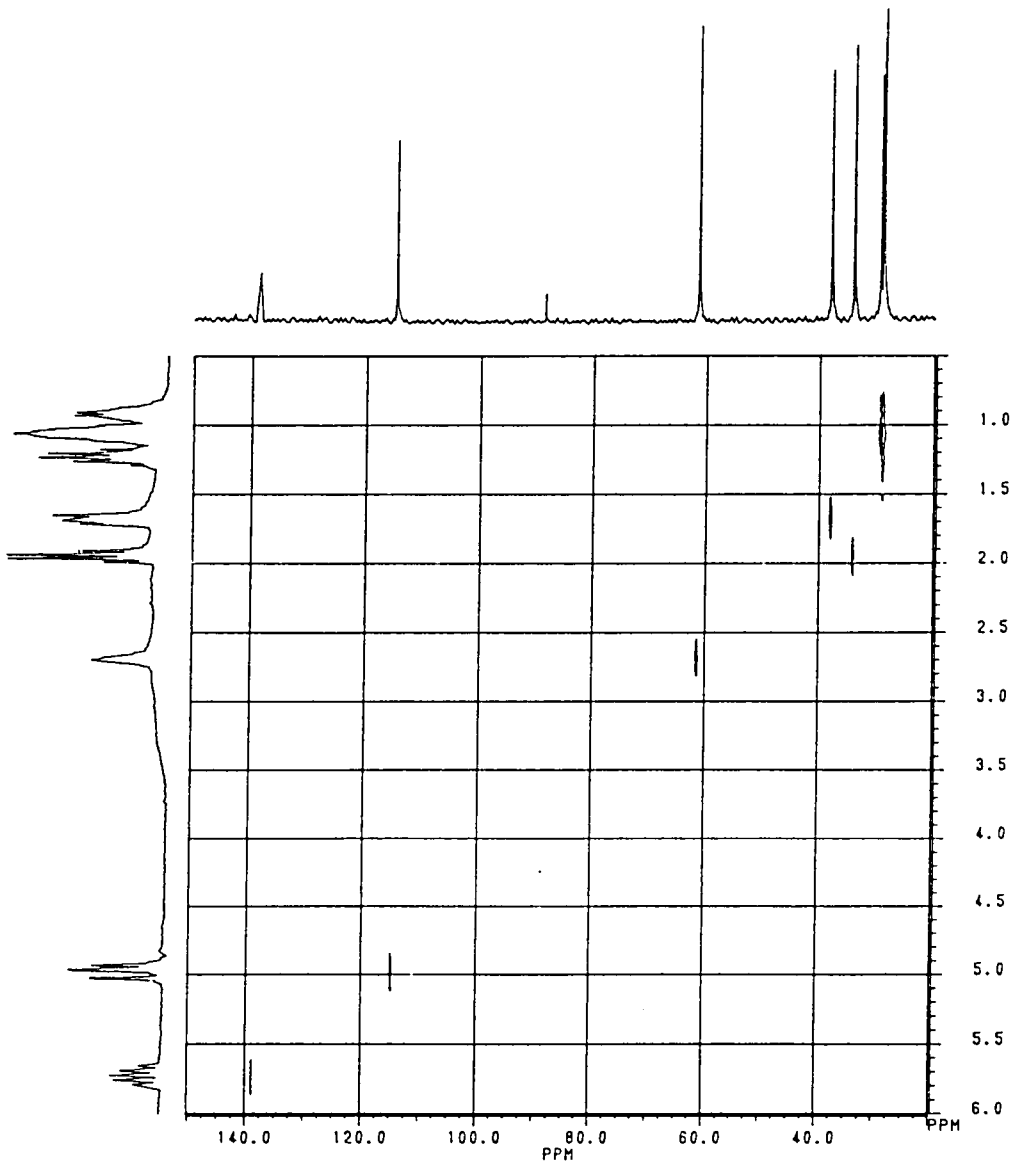


Figure 11. C/H COSY NMR spectrum of 1-(7-octenyl)-*o*-carborane (**10**).

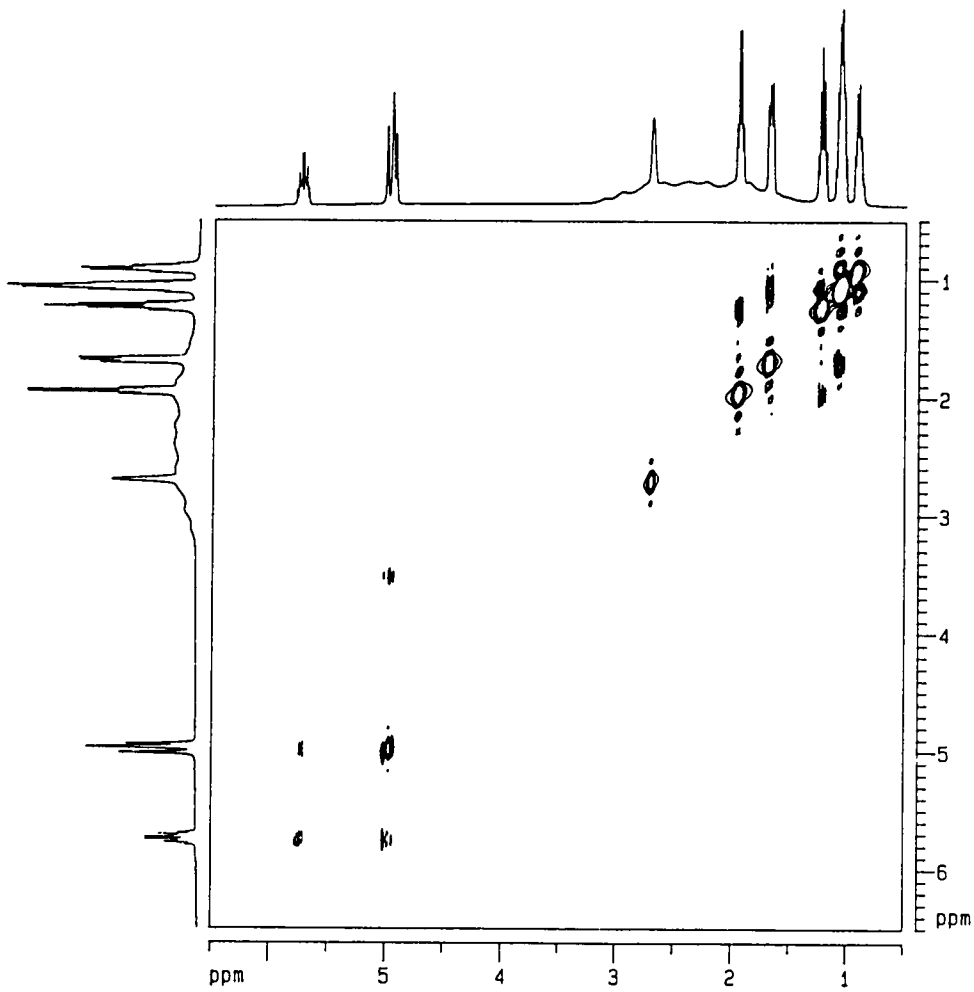


Figure 12. H/H COSY NMR spectrum of 1-(7-octenyl)-*o*-carborane (**10**).

CHAPTER III

The Hydroboration of 1-Vinyl Derivatives of *o*-Carborane

3.1 *Introduction*

The hydroboration of vinyl derivatives, $R_2C_\beta=C_\alpha HX$, can place the boron on both the α and β positions. Studies on the hydroboration of substituted styrenes revealed that the distribution of boron between the α and the β positions of the double bond was markedly influenced by the nature of the substituent (75,155). Thus, in *p*-methoxystyrene 7% of the boron was added to the α-position, whereas in *p*-chlorostyrene, the amount of α-addition was increased to 27%. Higher quantities of α-addition were observed, however, when the substituent was directly bonded to the double bond. Thus Seyferth,(156) reported a 37% α-addition for the hydroboration of trimethylvinylsilane (X = trimethylsilyl) with borane.

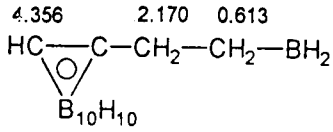
The hydroboration of 1-vinyl-*o*-carborane (X = *o*-carborane) is of particular interest, both with respect to reactivity and regioselectivity. The carborane cage is sterically bulky and should electronically deactivate the double bond towards hydroboration. Its ability, however, to stabilize adjacent negative charges should result in an enhanced α-boron addition. Thus, in this chapter the hydroboration of vinyl-*o*-carborane with representative hydroborating agents such as, BH_3·THF, Chx_2BH, and 9-BBN will be described. The hydroborations of 1-isopropenyl-*o*-carborane and *trans*-1-propenyl-*o*-carborane with BH_3·THF, which were also studied in order to assess the effect of a methyl group in the hydroboration of the 1-vinyl-*o*-carborane system, will also be described.

3.2 *Results*

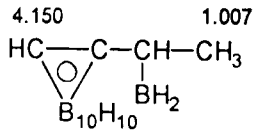
3.2.1 *The Hydroboration of 1-Vinyl-o-carborane with BH_3·THF in a 1:1 Molar Ratio.*

The hydroboration of 1-vinyl-*o*-carborane with BH_3·THF (1:1 molar ratio) at 25 °C was slow. Monitoring the reaction by ^1H NMR indicated a 70% conversion in 2 h and 100% in 6 h.

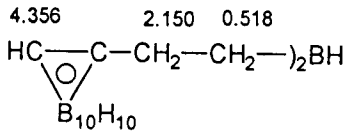
Since, the hydroboration reaction usually proceeds very rapidly to the trialkylborane stage despite the ratio of reagents used, the slow rate of this reaction provided the opportunity to follow the progress of the reaction by ^1H, ^{11}B, and ^{13}C NMR. Four intermediates (**VI-IX**) were detected during the reaction.



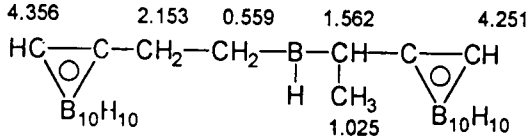
VI



VII



VIII



IX

Intermediates **VI** and **VII** formed early in the reaction and were major up to 50% conversion. Their ^1H NMR assigments are based in the following (Figure 13, Spectrum 1): the resonances at δ 0.613 (br m) and 4.356 (s) were assigned to the methylene protons in the CH_2-BH_2 group, and to the acidic C-H proton of the

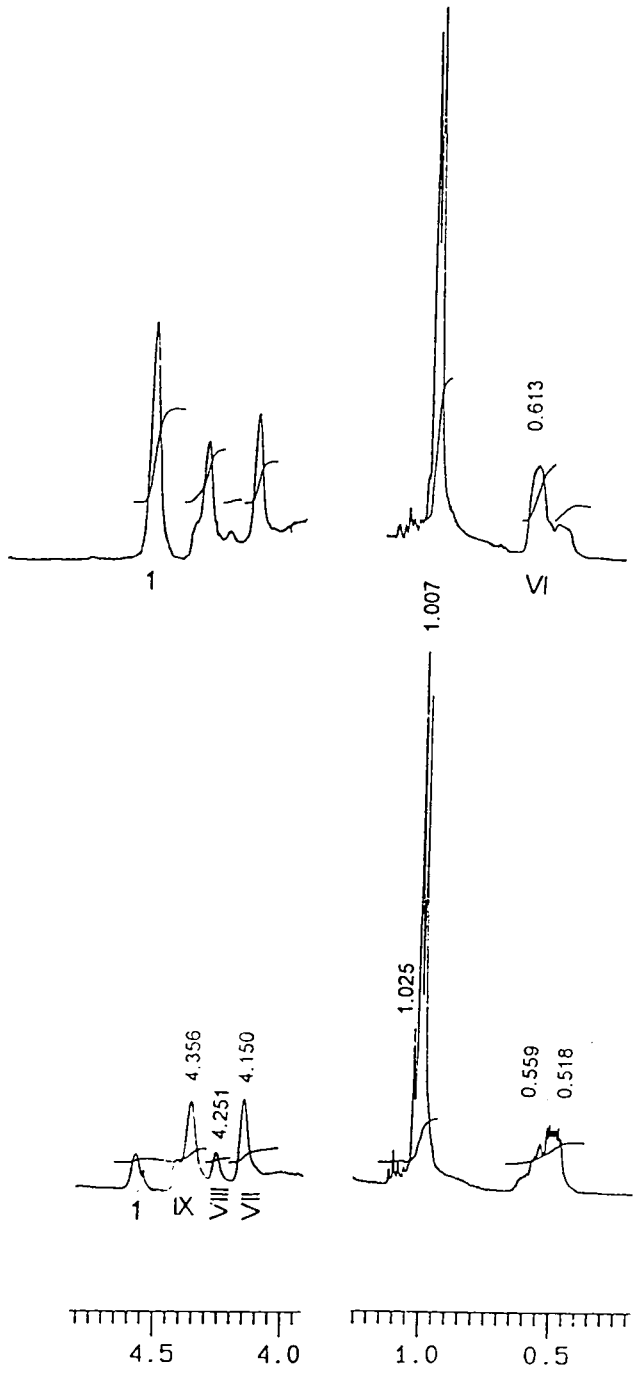


Figure 13. Partial ^1H NMR spectra of the intermediates in the hydroboration of vinyl-*o*-carborane with BH_3·THF (1 : 1 molar ratio).

carborane cage, respectively, in the terminal boron intermediate (**VI**). The doublet at δ 1.007 was assigned to the methyl group of the $CH(CH_3)BH_2$ moiety in **VII**, and the singlet at δ 4.150 was attributed to the corresponding cage C-H proton. Later in the reaction (70% conversion), the multiplet at δ 0.613 due to **VI** was considerably diminished, allowing the resonances at δ 0.559, and 0.518 (Figure 13, Spectrum 2) due to two additional terminal boron intermediates, **VIII** and **IX**, to be clearly observed. The unusually high coupling of the above signals (J = 4.4 - 5.2 Hz) is due to long range couplings of the methylene protons with the exopolyhedral borons in the CH_2BH_2 groups (157,158). Spectrum 2 (Figure 13), also shows a doublet at δ 1.025 and a singlet at δ 4.251, whose build up is followed by a concomitant decrease of the signals at δ 1.007 and 4.150 (this is best demonstrated in the 3:1 olefin: borane reaction which is discussed next). Due to the slow formation of R_3B intermediates in this reaction it is reasonable to assume that these changes are due to the formation of **VIII** from **VI** and **VII** by further reaction. Analysis of the NMR spectrum at 100% completion indicated an increase in the signals due to **VIII** and the disappearance of those assigned to **VI**.

The ^{13}C NMR spectrum at 100% conversion is tabulated in Table 12. The assignment of the resonances was based in part on a DEPT experiment. The data in Table 12 are typical of carborane compounds. Thus, the signals from δ 85.93 to 79.93 were due to the substituted carbon atoms of the carborane cages in the products (C-R), whereas those from δ 62.85 to 62.24 were due to the

Table 12. ^{13}C NMR of Products in the Reaction of **1** with BH_3·THF (1:1 ratio)

δ (ppm)	Assignment
85.93	Cage C-R
80.90	Cage C-R
79.93	Cage C-R
62.85	C-H
62.57	C-H
62.48	C-H
62.24	C-H
38.29	CH_2
37.70	CH_2
33.40	CH-B
30.88	CH-B
20.92	CH_2B
20.18	CH_3
19.35	CH_2B
18.46	CH_3

corresponding unsubstituted carbons (C-H). The signals at δ 79.93, 62.24, and 37.70 were tenantively assigned to intermediate **IX**, mainly because they underwent appropriate changes in area as a function of reaction time. For a similar reason the signals at δ 85.93, 80.90, 62.85, 62.48, 38.29, and 18.46 were assigned to intermediate **VIII**. The remaining signals (Table 12) at δ 85.93, 62.57, 30.88, and 20.18 were assigned to the internal boron intermediate, **VII**.

These assigments were supported by the H/C COSY experiment shown in Figure 14. Analysis of Figure 14 revealed that the two partially overlapping doublets at δ 1.025 and 1.007 in the proton projection correlated with the methyl groups at δ 18.46 and 20.18 in the carbon projection. As was stated earlier, this was consistent with the presence of two internal boron intermediates. Furthermore, the methylene signals at δ 38.29 and 37.70 in the ^{13}C projection correlated with the multiplets in the ^{1}H projection at δ 2.153 and 2.150 (due to two CH_2 groups next to the corresponding carborane cages), supporting the presence of two terminal boron intermediates. Finally, the C/H COSY indicated that two cage C-H protons overlaped at δ 4.356. Thus, in the ^{13}C projection the C-H resonances at δ 62.48 and 62.24 correlated with the proton signal at δ 4.356. According to the previous analysis these should be due to intermediates **VII** and **VIII**. Based on the analysis above, it was possible to estimate the percent composition of the intermediates in the late stages of the reaction (Table 13). Evaluation at the earlier stages was complicated by the overlap of signals due to **VI** and **IX**.

The data in Table 13 clearly show that intermediate **VI** is considerably more

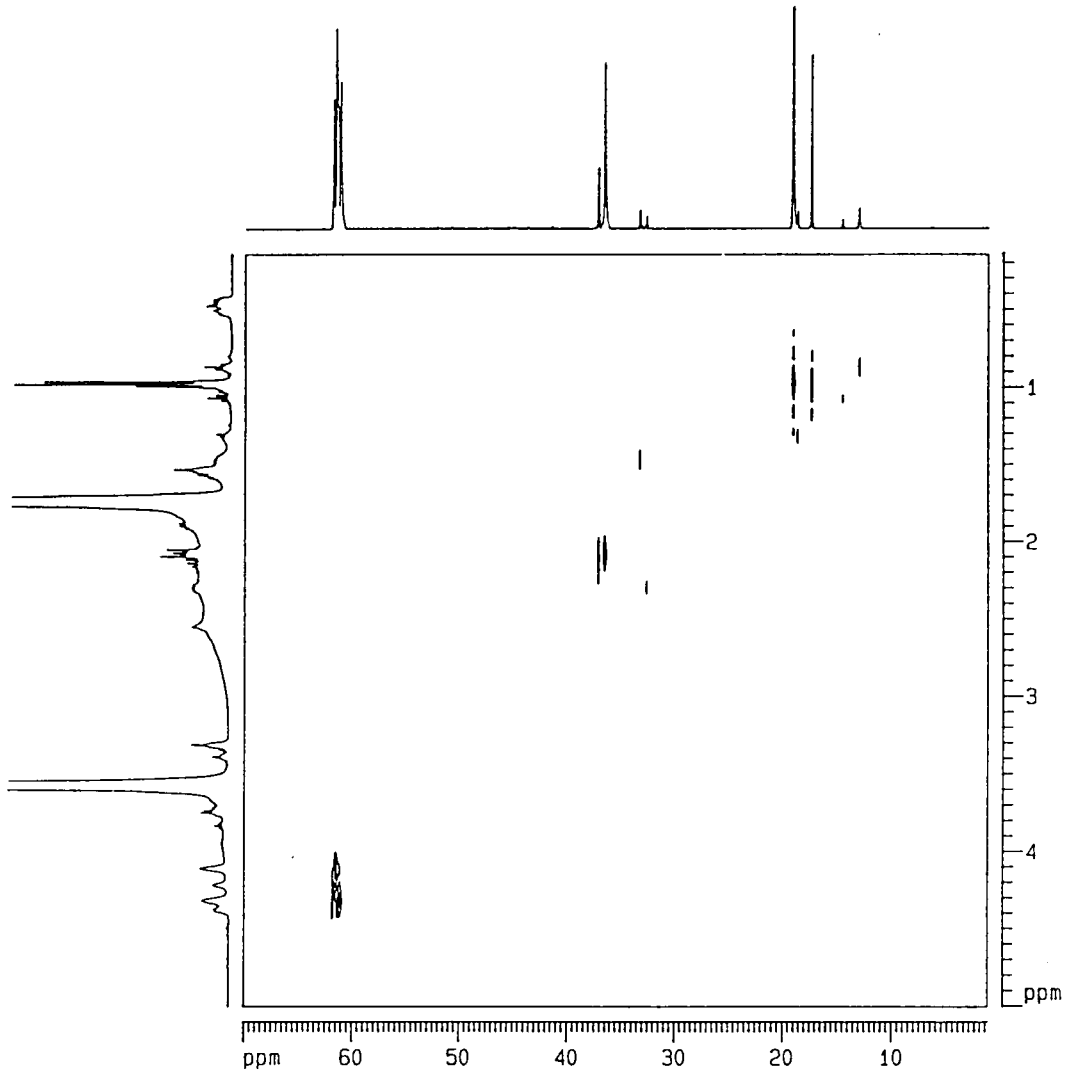


Figure 14. C/H COSY NMR spectrum of the intermediates in the hydroboration of vinyl-*o*-carborane with BH_3·THF (1 : 1 molar ratio).

reactive than **VII**, and that the boron distribution favors the internal carbon (56%).

Table 13. Percent Composition of Organoborane Intermediates Formed in the Reaction of 1-Vinyl-*o*-carborane with BH_3·THF (1:1 Molar Ratio).

	convertion 88%	100%
VI	0	0
VII	68	56
VIII	11	20
IX	21	24

An unexpected byproduct in the reaction, seen in the H/C COSY experiment had two broad resonances at δ 3.308 and 1.700 (^{1}H projection) which correlated with two methylene carbons at δ 71.13 and 27.54 (^{13}C projection). These results were consistent with a polymer formed from the solvent. Solvent complexation, which also could have taken place, would have resulted in a downfield shift from THF (^{1}H NMR), not the upfield shift observed.

The oxidation of the organoborane intermediates was performed with sodium perborate. The extent to which hydride was utilized during the hydroboration reaction was determined by addition of water to the reaction mixture prior to oxidation and measuring the resultant hydrogen gas volumetrically. The yield of the reaction products was calculated by ^{1}H NMR and by GC using dibromobenzene and tetradecane, respectively, as internal standards (Table 14). The signals used in the ^{1}H determination are listed in Table 15. In the GC experiment correction factors were calculated for all compounds except the suspected THF·carborane adduct.

Table 14. Percent Yield in the Reaction of 1-Vinyl-*o*-carborane with BMS (1:1 Molar Ratio).

Compound	^{1}H NMR	GC
Vinylcarborane	0	1.3
Ethylcarborane	9.9	8.4
1-Carboranylethyl alcohol	45.6	45.2
2-Carboranylethyl alcohol	39.5	43.6
Carboranyl·THF adduct	5	1.2
o-Carborane	0	0.3

Table 15. ^{1}H NMR Resonances[a] Used in the Yield Determination of Products[b].

Products	$\delta_{C\text{-}H}$ (ppm) (THF)
$C\underline{H}_3CH_2CB_{10}H_{10}C\text{-}\underline{H}$	1.089(t), 3.550 (s)
$C\underline{H}_3C\underline{H}(OH)CB_{10}H_{10}C\text{-}\underline{H}$	1.399(d), 4.277(s), 4.020(s)
$HOC\underline{H}_2CH_2CB_{10}H_{10}C\text{-}\underline{H}$	3.771(t), 6.008(s)

[a)]The underlined proton signals were used in the yield determination.
[b)]Measured in THF-d_8.

From the yields of alcohols and 1-ethyl-*o*-carborane the distribution of boron at the internal (a) and terminal (ß) carbon atoms of the vinyl side chain was 45% ß, 54% α by CG, and 42% ß, 58% α by ^{1}H NMR. In calculating these percentages the yield of 1-ethyl-*o*-carborane was added to that of the α-boron intermediate, as will be discussed later. When D_2O was added as a co-solvent during oxidation, up to 90% exchange of the C-H protons of the carborane cages in the products was observed. This was evidenced by ^{1}H and ^{13}C NMR spectroscopy, and by mass spectrometry.

3.2.2 *The Hydroboration of 1-Vinyl-o-carborane with BMS in a 3:1 Molar Ratio.*

The hydroboration of 1-vinyl-*o*-carborane with borane-methyl sulfide (BMS) (3:1 molar ratio) at room temperature proceeded at a slow rate, reaching the dialkylborane stage after 12 to 18 hours. The reaction mixture remained homogeneous at all times. The data of two kinetic runs are presented in Tables 16 and 17. In the first study, the loss of olefin was monitored by ^{1}H NMR relative to a known amount of dibromobenzene added as an internal standard. In the second, the loss of olefin was monitored by gas chromatography. Aliquots of the reaction mixture were quenched with a THF-H_2O mixture and the consumption of olefin was monitored relative to a known amount of hexadecane. As it can be seen, the two methods gave similar results. The ^{13}C NMR spectrum after 12 hours of reaction is tabulated in Table 18. The signals were assigned in part using a DEPT experiment. As is shown in Table 18, the major intermediates in the reaction were **VIII** and **IX**. Monitoring the reaction by ^{1}H NMR indicated a number of changes which were all in agreement with those reported earlier. Thus, at the onset of the reaction, three low field signals were detected at δ 4.356, 4.251, and 4.150. As the reaction progressed the signal at δ 4.150 slowly decreased until it completely disappeared, whereas the signals at δ 4.356 and 4.251 progressively increased Concomitantly, the methyl signal at δ 1.007 also decreased until it completely disappeared. This resulted in the formation of a methyl signal at δ 1.025 which increased with time. Downfield from this signal, at δ 1.100 an additional doublet was detected suggesting the presence of a previously undetected

Table 16. Reaction of 1-Vinyl-*o*-carborane (3.0 equiv) with BMS (1.0 equiv) in Tetrahydrofuran (THF) at 25 °C[a,b].

(%) 1-Vinyl-*o*-carborane Reacted	Time (hrs)
14	0.08
25	0.5
35	1
45	2
54	5
63	9
66	18
69	24

[a)]Determined by ^{1}H NMR.
[b)]1.28 mmol alkene (1.6 M), 0.427 mmol BMS (neat).

Table 17. Reaction of 1-Vinyl-*o*-carborane (3 equiv) with BMS (1 equiv) in Tetrahydrofuran (THF) at 25 °C[a,b].

(%) 1-Vinyl-*o*-carborane Reacted	Time (hrs)
20	0.08
32	0.5
42	1
50	2
55	4
65	9
70	24

[a)]Determined by GC.
[b)]3.3 mmol alkene (2.0 M), 1.10 mmol BMS (1.90 M).

Table 18. ^{13}C NMR Signals of the Organoborane Intermediates Formed in the Reaction of 1-Vinyl-*o*-carborane with BMS (3:1 Molar Ratio).

δ	Assignment
91.91	Cage C-R
86.60	"
86.19	"
*85.93	"
*80.23	"
*79.86	"
*79.63	"
64.42	Cage C-H
*62.79	"
*62.39	"
*62.16	"
*38.26	C
*37.65	"
*35.70	"
*33.27	$CH\text{-}BR_2$
21.59	CH_3
20.69	CH_2BR_2
20.10	CH_3
19.13	CH_2BR_2
18.59	CH_3
*18.44	"

*Major signals.

internal boron intermediate. C/H COSY and H/H COSY (Figure 15) experiments established that the doublet at δ_{H1} 1.100 ppm correlated with a peak at δ_{C13} 18.6 ppm and it coupled with a single proton at δ_{H1} 1.700 ppm. Similarly, the methyl group at δ_{H1} 1.025 ppm was shown to cross couple with a single proton (quartet) at δ_{H1} 1.562 ppm, in support of its earlier assigment (**VIII**). An attempt to follow the reaction with time, by ^{1}H NMR, was hindered due to the presence of unidentified peaks in the spectrum.

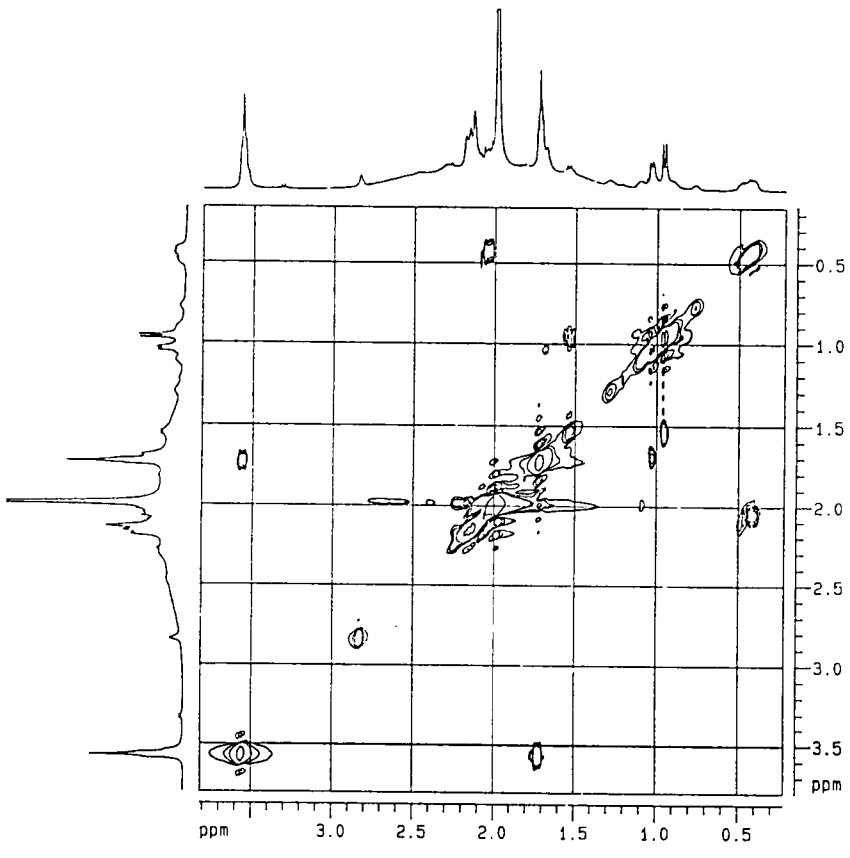


Figure 15. H/H COSY NMR spectrum of the intermediates in the hydroboration of vinyl-*o*-carborane with BH_3·THF (3 : 1 molar ratio).

The oxidation of the organoborane intermediates was carried out using both alkaline hydrogen peroxide and sodium perborate. The extent of hydride use by olefin was established by the addition of H_2O or H_2O/CH_3OH mixtures to convert the residual hydride to hydrogen gas. The total yield of products was generally good, varying between 86 to 95%. The upper limit was obtained using both oxidizing agents indicating an equal reactivity towards the organoborane intermediates. The yields were established by ^1H NMR integration using dibromobenzene as an internal standard. The results are summarized in Table 19. A major unpredicted byproduct in the reaction was 1-ethyl-*o*-carborane, formed by hydrolysis of the organoborane intermediates. As is shown in Table 20, the greatest quantity of 1-ethyl-*o*-carborane was obtained using alkaline hydrogen peroxide. When sodium perborate was used, yield of 1-ethyl-*o*-carborane was generaly lower, but it was variable. It appeared to increase with the quantity of water added to destroy residual hydride prior to oxidation, time of mixing, and whether or not CH_3OH was added as a co-solvent with water. The lowest yield of 1-ethyl-*o*-carborane was obtained when $NaBO_3$ was added in the minimum amount of water nessesary to bring it into solution. The internal boron intermediate was shown to be the precursor of both 1-ethyl-*o*-carborane and 1-carboranyl-1-ethanol (α-alcohol). Thus, in establishing the boron distribution between the α- and ß-positions of the 1-vinyl-*o*-carborane the amount of 1-ethyl-*o*-carborane was added to that of the α-alcohol. The overall yield shown in Table 20 includes the yield of 1-ethyl-*o*-carborane, isomeric alcohols, and in the case of entry 2, 3% of a byproduct believed to be an adduct of ethylcarborane with THF.

Table 19. % Distribution of 1-Ethylcarborane (EC), 1-Carboranyl-1-ethanol (α-OH), and 2-Carboranyl-1-ethanol (ß-OH) in 3:1 Hydroboration Reaction.

Oxidizing Agent	Total Yield(%)	EC%	α-OH%	ß-OH%	Boron Distribution(%) α	ß
$NaOH/OH^-$	93	31	23	46	54	46
$NaBO_3$	95	5	48	47	53	47

Table 20. Yields of Protonolysis in the Reaction of Vinyl-o-carborane with BMS (3:1).

Time of Hydroboration (h)	Reagent Added	%Residual Hydride	Oxidizing Agent	Total % Yield of Products	%Yield of Ethyl-o-carborane
5	None	-	$NaOH/H_2O_2$	90	* 49
18	H_2O/CH_3OH	34	$Na_2B_2O_3$	93	38
20	H_2O	34	Na_2BO_3	95	5

The mass spectrum of this product showed a base peak at 71 m/z, and a fragment ion at 169 m/z. No molecular ion was detected.

The large quantities of 1-ethyl-*o*-carborane in the products were attributed to the basic conditions utilized in the oxidation. It has been reported (75) that organoboranes of the benzylic type undergo facile hydrolysis of the α-boron derivatives under oxidation conditions. However, when the hydroboration reaction was quenched with MeOH, analysis using ^{13}C NMR revealed the formation of 1-ethyl-*o*-carborane, as evidenced by the signals at δ 13.66, 31.70, 61.72, and 77.62 in the spectrum. This was confirmed by an independent synthesis of 1-ethyl-*o*-carborane. When the experiment was repeated with MeOD, the signal at δ 31.70 was split into a triplet (J_{DC} = 20.6 Hz) due to deuterium incorporation on that carbon caused by the B-C cleavage. Along with the formation of 1-ethyl-*o*-carborane in the ^{13}C NMR spectrum the disappearance of all signals due to the intermediates containing internal boron groups, mainly **VIII**, was observed. These results were supported by ^{1}H NMR analysis, which showed the complete absence of doublets due to internal methyl groups in the spectrum.

$$\underset{\textbf{IX}}{(RCH_2CH_2)_2BH} + CH_3OD \rightarrow \underset{\textbf{XI}}{(RCH_2CH_2)_2BOCH_3} + HD \qquad (25)$$

$$\underset{\textbf{VIII}}{RCH_2CH_2BHCH(CH_3)R} + 2CH_3OD \rightarrow \underset{\textbf{X}}{RCH_2CH_2B(OCH_3)_2} + RCH(D)CH_3 + HD \qquad (26)$$

R = cage

The ^{11}B NMR spectrum of the MeOH treated intermediates showed two broad signals at δ 32.00 and 52.2 consistent with the esters **X** and **XI**, respectively (eq 25

and 26).

Since intermediates **VIII** and **IX** contained an active B-H bond it was of interest to examine their regioselectivities as hydroborating agents. Two monosubstituted terminal olefins were thus selected for hydroboration: 1-hexene and styrene. The results obtained for 1-hexene were as follows: 1-Vinyl-*o*-carborane was hydroborated with BMS (3:1 equiv) and the reaction allowed to proceed for 25 h. At the end of this period, the remaining active hydride (B-H) was estimated from the unreacted 1-vinyl-*o*-carborane as obtained by ^{1}H NMR, and the appropriate amount of 1-hexene was then added. The reaction was allowed to proceed for 2 hours while monitoring the reaction by ^{1}H, ^{13}C, and ^{11}B NMR. ^{11}B NMR spectroscopy indicated no trialkylborane intermediates. In fact, no signals appeared downfield from 0.00 ($BF_3 \cdot Et_2O$). Examination of the cage boron region, however, clearly indicated changes prior to and after addition of hexene. Similarly, evidence of reaction was observed in the ^{1}H NMR spectrum, which is tabulated in Table 21. In Table 21 the chemical shifts of the R_2BH intermediates were different from those reported earlier due to the presence of benzene added as an internal standard. The column to the left lists the signals with their assignments prior to addition of 1-hexene and to the right those after 1-hexene has been added. It is not clear why, upon addition of 1-hexene, the multiplet at 0.310 ppm remained unchanged, whereas that at 0.384 ppm disappeared. Perhaps this is related to the different reactivities of the R_2BH intermediates. Addition of methanol to the $R_2BC_6H_{13}$ intermediates resulted, once again, in the formation of 1-ethyl-*o*-carborane. Signals, in the

Table 21. ^{1}H NMR Spectra of the Products of Reaction of (Carboranyl)$_2$BH (R_2BH) with 1-Hexene.

R_2BH δ(ppm)	Assignment	(R_2BH+Hexene) δ(ppm)
4.278	C-H	4.267
4.083	C-H	4.150
4.030	C-H	4.035
0.883	CH_3	0.899
0.384	CH_2B	(gone)
0.310	CH_2B	0.310

^{1}H NMR spectrum due to 1-ethyl-*o*-carborane were at δ 0.918 (triplet, 3H), 2.135 (quartet, 2H), and 4.089 (singlet, 1H). ^{11}B NMR spectroscopy of the methanolysis mixture indicated two weak resonances at δ 52 and 31. These can be attributed to cleavage, as well as to incomplete hydroboration.

The oxidation of the organoborane intermediates was performed with sodium perborate. The yield of carborane products determined by ^{1}H NMR, relative to dibromobenzene added of as an internal standard, was 95%. No α-carboranylethyl alcohol was detected, in accord with the addition of CH_3OH prior to oxidation. The ratio of ß-carboranylethyl alcohol to 1-ethyl-*o*-carborane was 47:53, thus establishing the boron distribution at the ß- and α-carbon atoms. The yield of hexanol was only 70%. This could be due either to loss of product, or most likely to an incomplete hydroboration. The latter is consistent with ^{11}B NMR data. The regioselectivity of the addition of boron to 1-hexene was determined by GC analysis to be 97% terminal and 3% internal.

The hydroboration of styrene with the carboranylethylborane intermediates

was accomplished in a manner similar to that used for 1-hexene. The yield of phenylethyl alcohols was 86% as determined by GC analysis using hexadecane as an internal standard. The ratio of α- to ß-phenylethyl alcohols was 5:95.

Table 22 summarizes the directive effects of several hydroborating agents in the reaction with 1-hexene and styrene. Examination of the data shows that the organoborane intermediates from the 1-vinyl-*o*-carborane reaction with BMS exhibits similar directive effects as those observed using dicyclohexylborane. The lower selectivity of these dicarboranylalkylborane species compared to Sia_2BH is probably due to the reduced isomeric purity of the former in which up to 47% of the bulky carboranyl group is isolated from the boron atom by a methylene group.

Table 22. Directive Effects in the Hydroboration of 1-Hexene and Styrene with Selective Hydroborating Agents.

Olefin	Hydroborating Agent	Product Distribution(%) 1-ol	2-ol
1-Hexene	BH_3	94	6
	Sia_2BH	99	1
	Chx_2BH	97	3
	9BBN	>99.9	
	$(Carboranyl)_2BH$	97	3
Styrene	BH_3	80	20
	Sia_2BH	98	2
	9-BBN	98.5	1.5
	Chx_2BH	95	5
	$(Carboranyl)_2BH$	95	5

3.2.3 *The Hydroboration of 1-Vinyl-o-carborane with Dicyclohexylborane(Chx_2BH) in 1:1 Molar Ratio*

The hydroboration of 1-vinyl-*o*-carborane with Chx_2BH in THF (1 : 1.1 molar ratio), at 25 °C led to a slow reaction, which reached an 88% conversion in 20 hours. Oxidation of the products with sodium perborate yielded carborane alcohols in a 88% yield. This was determined by ^1H NMR integration relative to an internal standard. In the ^1H NMR spectrum, besides the resonances of the alcohols, there was a quintet-like absorption at 3.910 ppm attributed to radical produts(10%). A small amount of 1-ethyl-*o*-carborane (2%) was also detected. GC/MS analysis showed, besides alcohols, two late eluting peaks at 17.9 and 22.3 min, which in their mass spectra had base peaks at 71 amu and 83 amu. These peaks were attributed to coupling products of THF and Chx_2BH with ethylcarborane respectively (160). When the crude product was treated with *N,O*-bis(trimethylsilyl)trifluoroacetamide (BSTFA), analysis of the resulting mixture by GC/MS gave a 98:2 ratio of primary to secondary alcohols.

3.2.4 *The Hydroboration of 1-Vinyl-o-carborane with 9-BBN in THF*

The hydroboration of 1-vinyl-*o*-carborane with 9-BBN in THF (1 : 1.1 molar ratio) proceeded very slowly at 25 °C. The reaction was repeated using ultrasound (159) at 30-35 °C and the loss of the olefin was monitored by ^1H NMR relative to an added internal standard. The reaction was found to be 50% complete in 6 hours and 92% in 24 hours. ^1H NMR monitoring of the reaction indicated a smooth conversion to products. Thus, the cage C-H proton of the starting material at 4.198 ppm (C_6D_6)

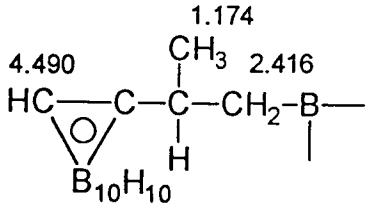
slowly disappeared with the concomitant formation of a similar signal at 4.097 ppm. This is in sharp contrast with the variety of signals observed in this region in the hydroboration of 1-vinyl-*o*-carborane with BMS. In the high field region of the spectrum two signals were observed at 2.211 ppm and 0.985 ppm (integrating for two protons each). These signals were assigned to the ethylene side chain of the carborane group in the trialkylborane intermediate (B-R-9-BBN). The ^{11}B NMR results, however, were less clear. The disappearance of the signal due to 9-BBN at 28 ppm was accompanied by the formation of a broad signal at 45.6 ppm. At no instance was a peak found at 85 ppm, which is where a typical B-R-9-BBN resonates. Oxidation of the reaction intermediates with sodium perborate gave 97% yield of alcohols and 3% yield of 1-ethyl-*o*-carborane, as determined by ^1H NMR using dibromobenzene as an internal standard. The overall yield of carborane products was 93%. Treatment of an aliquot of the crude product with BSTFA gave by GC/MS analysis, 2-carboranyl-1-ethanol and 1-carboranyl-1-ethanol in a 99:1 ratio.

3.2.5 *The Hydroboration of 1-Isopropenyl-o-carborane with BH_3·THF.*

The hydroboration of a carefully degassed sample of 1-isopropenyl-*o*-carborane with BH_3·THF (3 : 1.1 molar ratio) in THF proceeded slowly at 25 °C. The rate of loss of olefin was monitored using ^1H NMR relative to dibromobenzene added as internal standard. Thus, the reaction was 40% complete in 0.5 h, 50% in 0.8 h, 63% in 2.6 h, and 73% in 16 h.

The major signals in the ^1H NMR spectrum at 40% completion were those

due to the 2-carboranyl-1-propylborane intermediate (**XII**).



XII

A singlet was detected at 4.490 ppm due to the cage C-H proton, a highly coupled multiplet at 2.416 ppm due to a CH_2 group α to the cage, and a doublet at 1.174 ppm (J = 6.8 Hz) due to an internal methyl group. At 63% completion the spectrum became more complex.

Examination by ^{13}C NMR (Table 23) at 40% conversion revealed several signals of which the major, at δ 84.01, 62.25, 37.21, and 23.24, were due to the 2-carboranyl-1-propyl group. This assignment was established by DEPT and C/H COSY experiments. No methyl signals due to internal boron intermediates were detected. Examination by ^{11}B NMR at 40% conversion showed a broad singlet at 8.107 ppm which disappeared at 60% conversion.

The oxidation of the products of hydroboration was performed with alkaline hydrogen peroxide. Analysis by ^{1}H NMR, relative to a known amount of dibromobenzene, indicated the exclusive formation of the primary alcohol in 90% yield. This value is corrected for 22% unreacted starting material. In addition to the alcohol, 2-carboranylpropane (6%), and *o*-carborane were also detected in the

Table 23. ^{13}C NMR Signals of the Organoborane Intermediates in a 3:1 Reaction.

δ	Assignment
86.11°	Cage C-R
84.01	"
62.25°	Cage C-H
61.74°	"
40.54°	CH
37.21	"
23.24°	CH_3
21.67°	"

°Major signals at 40% convertion

products. ^{13}C NMR analysis revealed signals due to 2-carboranyl-1-propanol at 81.78 ppm (substituted cage carbon), 65.15 ppm (methylene carbon), 61.08 ppm (unsubstituted cage carbon), 41.32 ppm (methine carbon), and 17.31 ppm (methyl carbon). A signal due to *o*-carborane was detected at 55.93 ppm. The assignment of the major product of the reaction as 2-carboranyl-1-propanol was also supported by C/H COSY NMR. The results obtained are summarized in Table 24. The carbon signals on the left were found to cross-correlate with the proton signals listed to their right. The results in Table 24 show that the proton signals at δ 3.627 and 3.509 belong to a single methylene group with a ^{13}C NMR chemical shift at δ 65.15, a typical value for the CH_2OH moiety. This clearly shows that these protons share a diastereotopic relationship and provides further support for the assignment.

Table 24. Heteronuclear H/C COSY Cross Correlation Experiment of 2-Carboranyl-1-propanol.

δ_C	δ_H	Coupling Assignments
81.78	-	-
65.15	3.627/3.509	multiplet
61.08	4.816	singlet
41.32	2.571	multiplet
17.31	1.150	doublet

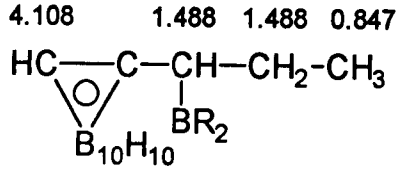
GC/MS analysis of an aliquot of the crude products, after treatment with BSTFA, indicated the exclusive formation of the trimethylsilyl ether of 2-carboranyl-1-propanol. No secondary isomer was detected. Thus, the GC/MS spectrum indicated an ion cluster with a high mass cut-off peak at 262 amu and a base peak

at 103 amu. The former is due to the loss of a CH_3 radical from the molecular ion, a typical cleavage of trimethylsilyl ethers, and the latter is due to the fragment $CH_2=O^+$-Si-$(CH_3)_3$. In addition, GC/MS analysis confirmed the formation of *o*-carborane as well as a small amount 2-carboranylpropane. If the latter were produced by C-B cleavage of an α boron intermediate, it would mean that the addition of boron to the double bond is not a regiospecific process. In a separate experiment, however, in which the oxidation of the intermediate was accomplished with sodium perborate, examination of the products by ^{1}H NMR failed to show either of the above byproducts or internal alcohol. This then excluded the presence of α boron intermediates in the reaction mixture. The formation of *o*-carborane can reasonably be explained by elimination from the ß boron intermediates under the strongly alkaline conditions utilized in the H_2O_2/OH^- oxidation. Since no peaks due to *o*-carborane were detected by either ^{13}C or ^{1}H NMR during the hydroboration, the spontaneous elimination of the *o*-carborane moiety was ruled out.

3.2.6 *The Hydroboration of 1-Propenyl-o-carborane with BH_3·THF.*

The hydroboration of 1-propenyl-*o*-carborane with BH_3·THF (3 : 1.1 molar ratio) proceeded rapidly to the monoalkylborane, but very slowly beyond that stage. Monitoring the reduction of the cage C-H proton in the olefin by ^{1}H NMR revealed that the reaction was 32% complete in 0.5 h, 47% in 12 h, and 56% in 36 h.

Examination of the ^{1}H NMR spectrum of the organoborane intermediates revealed that **XIII** was clearly the major product. The spectrum contained a singlet at 4.108 ppm due to a cage C-H proton, two overlapping multiplets at 1.488 ppm due



XIII

to -CHB and -CH_2 groups, and finally a triplet at 0.847 ppm due to a -CH_3 group. The area ratio of the these signals was 1:3:3. Furthermore, the coupling constant of the triplet (J = 7.2 Hz) was identical to one of the coupling constants observed in the multiplet at 1.488 ppm. Thus, the CH_3CH_2- fragment was confirmed. The remaining hydrogen in the multiplet at 1.488 ppm was adjacent to a boron since a second coupling constant of J = 4 Hz was observed. This was indicative of a long range coupling to boron.

The ^{13}C NMR spectrum of the hydroboration product was also in agreement with this assignment. The results are summarized in Table 25.

Table 25. ^{13}C NMR Spectrum of the Major Product of the Reaction of 1-propenyl-*o*-carborane with BH_3·THF (THF-d_8)

δ_{13}	Assignment
86.36	Cage C-R
62.76	Cage C-H
~39.00	-CHB
28.46	CH_2
14.62	CH_3

The results summarized in Table 25 clearly demonstrate the deshielding effect of a secondary carbon on the resonance of the adjacent carbon atom of the carborane cage. This is consistent with the assumption made earlier in studies of the hydroboration of 1-vinyl-*o*-carborane in which the signals at ≈86 ppm were assigned to α-boron intermediates.

As was the case in the hydroboration of 1-vinyl-*o*-carborane, solvent polymerization occurred during the reaction as evidenced by broad singlets in the ^{1}H NMR spectrum at 3.259 ppm and 2.477 ppm. In the ^{13}C NMR spectrum, the corresponding signals were at 71.17 ppm and 27.58 ppm. This product was first observed 6 h into the reaction and increased ten-fold after 25 h. Monitoring of the ^{11}B NMR spectrum indicated an absence of a trialkylborane species. However, a broad signal was observed at 6.43 ppm, possibly due to a complexed monoalkylborane intermediate. Such a signal was not present in the spectrum of either the olefin or the hydroborating agent. A weaker signal was also observed at 18.85 ppm. This could either be due to an impurity or to a dimeric monoalkylborane species. The two signals taken together could represent a monomer-dimer equilibrium mixture in which the monomeric species predominates (89%).

Examination of the boron signals due to the cage atoms indicated a mixture of starting material and the hydroboration product. The signals due to boron atoms B(12), B(8,10), B(3,6), B(4,5), and B(7,11) showed little difference between the two species. Thus, they resonated at δ -4.43, -8.42, -9.96, -10.11, and -11.80. However a considerable upfield shift of δ -1.36 (from -1.394 to -2.753) was observed for B(9)

in the products. This is rather unusual because, in the ^{11}B NMR spectra of carbon substituted carboranes, the "*para*" boron undergoes the "*antipodal*" effect which is shielding in nature. The effect on the "*meta*" borons is considerably smaller and can be either shielding or deshielding depending on the substituent. In the present case, a shielding effect was observed for the "*meta*" boron B(9) and no effect for a "*para*" B(12).

Oxidation of the reaction mixture by a simultaneous addition of sodium hydroxide and hydrogen peroxide at 0 °C, followed by stirring at 25 °C for 12 h, afforded carborane products in 96% yield. Analysis by ^1H NMR, using a known amount of dibromobenzene as internal standard, indicated a distribution of products as follows; 1-carboranyl-1-propanol (71%), 1-carboranyl-2-propanol(8%), 1-(*n*-propyl)-*o*-carborane (18%), and *o*-carborane (3%). It is assumed that the 1-propyl-*o*-carborane arises from a facile hydrolysis of the α-boron derivative under the oxidation conditions. On the other hand, *o*-carborane likely arises under similar conditions by elimination of either the α- or the ß-boron intermediates. The boron distribution at the α- and ß-positions of the double bond was 90% and 10%, respectively. The formation of *o*-carborane in the products was supported by ^1H NMR, ^{13}C NMR, and GC/MS data. Thus, in the ^1H NMR (acetone-d_8) and ^{13}C NMR ($CDCl_3$) spectra singlet absorptions were detected at 4.497 and 54.65 ppm, respectively. The GC/MS spectrum of the crude products showed a molecular ion cluster which had a maximum intensity peak at 143 amu and high mass cut-off peak at 146 amu.

The carborane products in the reaction were separated from the polymeric material by extraction with acetone in which the latter was insoluble. ^{1}H NMR ($CDCl_3$) analysis of the polymeric product revealed two broad singlets at δ 3.413 and 1.619. Similarly, the ^{13}C NMR ($CDCl_3$) spectrum revealed two signals at δ 70.50 and 26.42. Addition of THF resulted in two additional signals in the ^{13}C NMR spectrum at δ 67.82 and 25.46.

3.3 *Discussion*

The hydroboration of 1-vinyl-*o*-carborane with borane proceeds to place 45%(±2) of the boron at the ß-position and 55%(±2) at the α-position. The large quantity of α-boron addition is another indication of the powerful electron withdrawing ability of the *o*-carboranyl group. This effect is exerted mostly by an inductive mechanism but, as it was pointed out earlier, a resonance contribution by conjugation of the p-orbital of the vinyl group and the p-type orbital of the cage cannot be excluded. Such a mechanism would increase the positive charge on the carbon beta to the cage, thereby favoring hydride addition to that carbon. Comparison with the data in Chart 7 (Chapter I, pg 15) indicates that the electronic effect of the *o*-carboranyl moiety should be similar to that of chlorine. Furthermore, comparison with Chart 13 (Chapter I, pg 18) shows that the selectivity for the α-position exhibited with 1-vinyl-*o*-carborane is greater than that of styrene and better compares with that of 3-vinylpyridine. The ß boron intermediate was found to be stable towards elimination even under alkaline conditions. The α boron intermediate, on the other hand, was especially susceptible to protonolysis owing to

the strong electron-withdrawing properties of the cage. A similar situation was observed with 3-vinylpyridine, which gave 34% protonolysis under alkaline hydrogen peroxide oxidation (82). However the formation of alkyl-*o*-carboranes in the present case was nearly eliminated by the employment of sodium perborate as the oxidizing agent. Thus, with 1-vinyl-*o*-carborane a remarkable reduction in the yield of ethyl-*o*-carborane was detected, decreasing from 49% with H_2O_2/OH^- to 5% with $NaBO_3$. Hydroboration with Chx_2BH and 9-BBN resulted, as anticipated (Chart 13, Chapter I, pg. 18), in 97% and 96% addition of boron to the terminal carbon atom. Obviously, the role of the electronic effect of the cage is largely nullified by the large steric effects of these reagents.

Despite the large electron-withdrawing effect of the carboranyl group, introduction of a methyl group vicinal to the cage, as in 1-isopropenyl-*o*-carborane, was sufficient to bring about the reversal of direction of addition resulting in placement of the boron exclusively at the terminal carbon atom. This could be attributed to both the steric effects of the *o*-carborane cage and the electronic effects of the methyl group, both operating in the same direction. To the extent that the transition state involves the development of an electron deficiency at the internal carbon, the presence of the methyl group is favorable due to its ability to stabilize the charge adjacent to it by hyperconjugation. Similar results were obtained in the hydroboration of α-methylstryene and 1,1-diphenylethylene (42).

In the case of the *trans*-1-propenyl-*o*-carborane, the 90% α and 10% ß boron distribution is due to the combined (-I) effect of the carboranyl cage and the methyl

hyperconjugative effect, both of which act to decrease the amount of electron density at the ß-position and to increase it at the α-position. The data in Chart 13 (Chapter I, pg 18) indicates that the directive effect of the carboranyl group for the α-position is greater than in *trans*-1-propenylbenzene, but less than *trans*-2-(1-propenyl)pyridine.

During oxidation of 1-isopropenyl-*o*-carborane and *trans*-1-propenyl-*o*-carborane with H_2O_2/OH^-, a base catalyzed elimination to 3-4% of *o*-carborane was observed presumably for the ß boron intermediate. However, when the oxidation was carried out with $NaBO_3$, the production of *o*-carborane was avoided.

CHAPTER IV

Hydroboration of C(1)-Alkenyl Derivatives of *o*-Carborane Carrying a Double Bond ß to the Cage.

4.1 *Introduction*

In the hydroboration of representative allyl derivatives, it has been shown that the substituents exert a profound effect on the direction of addition of borane to the double bond. The percent addition of the boron to the internal carbon atom decreases with decreasing electronegativity: allyl tosylate, 45%; allyl chloride, 40%; allyl acetate, 35%; allyl benzoate, 25%; and allyl borate, 18%. Methyl substitution on the terminal carbon of the allyl system greatly increases the addition of the boron at the position closest to the electronegative substituent: crotyl chloride, 100%; crotyl acetate, 95%; crotyl benzyl ether, 91%; crotyl alcohol, 90%; and crotyl ethyl ether, 84%.

The main objective in this chapter is to examine the effect of the *o*-carboranyl group on the direction of addition of borane to allyl and crotyl groups. 1-Allyl-*o*-carborane, 1-allyl-2-hexyl-*o*-carborane, and 1-crotyl-*o*-carborane were selected as representative derivatives. Dicyclohexylborane, and 9-borabicyclohexyl[3.3.1]nonane were used in the hydroboration reactions in order to minimize the directive influence of the substituent and to maximize the addition of boron to the less substituted carbon atom.

4.2 *Results*

4.2.1 *Hydroboration of 1-Allyl-o-carborane with BH_3·THF.*

The hydroboration of 1-allyl-*o*-carborane with BH_3·THF in THF (3:1 molar ratio) at 25 °C proceeded rapidly. Monitoring the reaction by ^1H NMR indicated that the disappearance of the vinyl protons in the alkene was 73% complete in 5 min, 92% in 20 min, 97% in 35 min, and 99% in 60 min. In a similar study in benzene, the rate of the reaction was found to be considerably slower. Thus, when a 0.92 M solution of the olefin was hydroborated at 25 °C in benzene, ^1H NMR analysis indicated that the reaction was 61% complete in 15 min, 77% in 60 min, and 94% in 180 min. At 80% conversion, a white needle-like precipitate was detected. Precipitation is normally observed with dialkylborane dimers. Monitoring the reaction in THF using ^{11}B NMR spectroscopy indicated, upon considerable magnification of the spectrum, a weak broad signal at δ 85 due to tricarboranylborane intermediates. Upfield from BF_3·OEt_2, signals due to the cage boron atoms underwent minor changes. The signals due to B(4,5) at δ -11.70 and B(3,6,7,11) at δ -12.56 in the starting material were broadened and coalesced into a singlet, whereas the signal due to B(12) at δ -6.124, (antipodal boron) was significantly relaxed. The resonances due to B(9) and B(8,10) at δ -2.980 and -9.735 did not show any appreciable change. The ^{11}B NMR spectrum of the reaction run in benzene revealed identical results. No evidence of dialkylborane intermediates was observed. To investigate further, methanol was added and the products examined by ^{11}B NMR. No signals due to boronate (~32 ppm) or borinate (~51

ppm) esters were observed even under magnification.

The oxidation of the products of hydroboration in THF was carried out, at 25 °C for 12 h, by both alkaline hydrogen peroxide and by sodium perborate. The results of a comparative study are presented in Table 26. Analysis by ^{11}B NMR indicated 3% cage degradation using H_2O_2/OH^-, but only a trace amount (< 1%) was formed using $NaBO_3$. This was evidenced by signals at δ -15.84, -17.01, -20.82, -32.03, and -35.85, which are typical of *nido* carboranes. The ratio of primary to secondary alcohols (^1H NMR) obtained using sodium perborate oxidation was 66:34 whereas with alkaline hydrogen peroxide, a 64:36 ratio was obtained. These were average values of three ^1H NMR determinations.

^1H NMR spectroscopy of the organoborane intermediates in THF-d_8 revealed that the cage C-H protons of the intermediates overlapped at δ 4.270. The results of H,C COSY experiment (Table 27) indicated the presence of at least three such intermediates. This is consistent with the number of reasonable intermediates expected if the reaction had proceeded to the trialkylborane stage. Several signals were present in the high field region of the ^1H NMR spectrum, the major ones occuring at δ 2.233 to 2.135 and δ 0.910 to 0.729 , due to the CH_2-CH_2 groups in the intermediates. In the latter group of signals, a doublet due to a methyl group was also clearly present at δ 0.783 (J_{HH}=7.2 Hz).

Examination by ^{13}C NMR revealed resonances due to at least five alkylcarborane groups. This conclusion is supported by five signals observed at 80-76 ppm due to C-R cage carbon atoms. The results are summarized in Table 28. The

Table 26. Comparison of the Sodium Perborate and Hydrogen Peroxide Oxidations in the Hydroboration of Allyl-*o*-Carborane with BH_3·THF.

Oxidizing agent	Time (h)	Total yield[a]	Alcohol yield[a] %	Boron distribution ß	Boron distribution γ	Propyl[a] carborane yield, %	% Other radical Products
$NaBO_3$	12	96	91	34	66	9	-
H_2O_2/OH^-	12	97	85	36	64	6	9

[a]Determined by ^1H NMR, using dibromobenzene as internal standard.

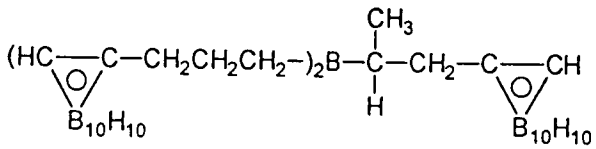
Table 27. C/H COSY of the Products of Hydroboration of Allyl-*o*-Carborane with BH_3·THF in THF at 25°C.

δ_{C13}	δ_{H1}	Assignment
63.62	4.27	CH(s)
63.10	4.27	CH(s)
62.80	4.27	CH(s)
43.39	2.42	CH_2(m)
42.19	2.18	CH_2(m)
41.90	2.23	CH_2(m)
41.06	2.10	CH_2(m)
23.70	0.49	CH_2-B(m)
16.30	0.79	CH_3(d)
15.82	0.88	CH_3(d)
15.36	0.74	CH_3(d)

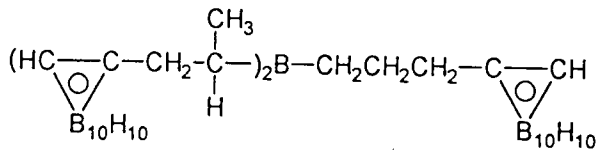
Table 28. ^{13}C NMR Spectrum of the Products of Hydroboration of Allyl-*o*-Carborane with BMS at 25 °C in THF-d_8

δ_{C13}	Assignment
78.37	Cage C-R
77.69	"
77.34	"
76.98	"
76.58	"
63.62	Cage C-H
63.10	"
62.80	"
43.39	CH_2
42.19	CH_2
41.90	CH_2
41.06	CH_2
29.19	C-B
26.74	CH_2
26.39	CH_2
23.70	C-B
15.82	CH_3
15.36	CH_3

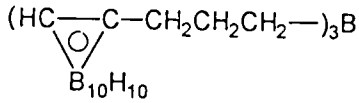
assignments are supported by the results of a DEPT experiment. Based on the intensity ratios and the chemical shift values, the signals due to the cage substituted carbons were assigned to three intermediates as follows: 78.37 and 76.98 ppm are due to a mixed organoborane consisting of one-internal and two terminal boron groups **XIV**, 77.69 and 76.58 ppm are due to two internal and one terminal boron groups **XV** and finally, 77.34 ppm is due to a tri-terminal boron intermediate **XVI.**



XIV



XV



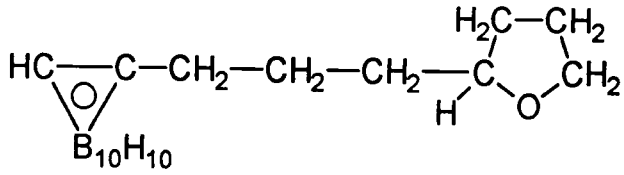
XVI

The intensities of the signals in the aliphatic carbon region of the spectrum were consistent with these assignments. Thus, the remaining signals due to **XIV** could be assigned as follows: 43.39 ppm and 15.36 ppm are due to the CH_2 and CH_3 groups in the secondary alkylcarboranyl moiety of the intermediate; 41.70 ppm and 26.40 ppm are due to the -CH_2CH_2- unit in the corresponding primary group.

Monitoring the ^1H NMR spectrum in benzene was more indicative of the

changes that took place during the reaction. Thus, three signals due to the cage C-H groups of the organoborane intermediates were detected at δ=3.16, 3.11, and 3.04. However these signals, could not be followed during the reaction because they partially overlapped with the broad B-H signals of the cage. In the high field region of the spectrum three doublets were observed at δ 0.969, 0.921, and 0.749, each with a coupling constant (J_{HH}) of 7.2 Hz. At 60% conversion the reaction was still homogeneous and the combined peak areas indicated 33% of products. This is in excellent agreement with the 35% secondary alcohol observed in the reaction. A more careful evaluation of these integrals, correcting for the appropriate number of methyl protons in each intermediate and excluding a tri-internal boron intermediate as major product, enabled the establishment of the composition in the reaction as 24% $(RCH_2CH_2CH_2)_3B$ **(XVI)**, 64% $(RCH_2CH_2CH_2)_2BCH(CH_3)CH_2R$ **(XIV)**, 7% $R(CH_2)_3B(CH(CH_3)CH_2R)_2$ **(XV)**, and 5% $B(CH(CH_3)CH_2R)_3$ **(XVII)**.

When the precipitate obtained in benzene was dissolved in THF under an inert atmosphere, a very exothermic reaction occurred indicative of complexation. GC/MS examination of this solution indicated the presence of a small amount of product (~5%) which had a base peak at 71 amu. No molecular ion (M^+) ion was detected. The amount of this product seemed to increase during exposure to air. The ^{13}C NMR spectrum of a very dilute sample of this adduct revealed aliphatic signals at δ 76.66 (CH), 67.46 (CH_2), 38.10 (CH_2), 31.56 (CH_2), 34.91 (CH_2), 26.30 (CH_2), and 25.76 (CH_2) ppm. No carborane cage carbon resonances were detected. Nevertheless, these data are consistent with the compound shown next.



In one experiment, the reaction was run in a THF-d_8/THF solvent mixture and, prior to oxidation, was examined by GC/MS to reveal only a small amount of protonolysis products. When, however, the reaction was exposed briefly to air, GC/MS revealed the presence of two compounds which had base peaks at 71 and 78 amu. These results clearly established the presence of THF and THF-d_8-alkylcarborane adducts in the reaction mixture and confirmed their free radical origin. Examination of the mass spectrum of the protonolysis product for deuterium incorporation was inconclusive. The formation of the protonolysis product should also be a free radical process initiated by trace amounts of oxygen in the reaction mixture (160). Treatment of the organoborane intermediates with base at 30 °C for 1 h failed to increase the amount of protonolysis as evidenced by ^{1}H and ^{13}C NMR.

4.2.2 *Hydroboration of 1-Allyl-o-carborane with 9-BBN in Hexanes.*

Hydroboration of 1-allyl-*o*-carborane, with 9-BBN in hexanes (1:1 molar ratio) under ultrasound at 30 °C, proceeded smoothly to the trialkylborane stage. ^{11}B NMR spectoscopy revealed the appearance of a signal at 87.40 ppm due to the trialkylborane intermediate and indicated that the reaction was 34% complete in 0.5 h, 67% in 2 h, and 100% in 3.5 h. The reaction at 25 °C, under normal conditions, was shown to be considerably slower.

The mass spectrum of the intermediate exhibited a $M^{+\cdot}$ cluster of high mass cut-off peak at 308 amu and a base peak at 121 amu. Thus, the mass spectrum corresponded to that expected for the (B-R-9-BBN) adduct. This is consistent with H,C COSY and DEPT experiments, the results of which are summarized in Table 29.

Table 29. ^{13}C NMR, H/C COSY, and DEPT Results of the Organoborane in the Reaction of 1-Allyl-*o*-carborane with 9-BBN (Benzene-d_6)

δ_{C13}	δ_{H1}	Assignment
75.89		Cage-CR
61.35	3.00	Cage-CH
40.94	1.97	-CH_2
33.64	1.93	-CH_2(9-BBN)
31.33	1.74	-CH(9-BBN)
27.40	–	CH_2-B
24.74	1.60	-CH_2
23.54	1.36	-CH_2(9-BBN)

As can be seen in Table 29 the signals at δ 40.94, 24.74, and 27.40 can reasonably be assigned to the α, ß, and γ methylene groups attached to the cage, respectively. The signal at 27.40 ppm was considerably broadened indicating its direct bonding with the exopolyhydral boron.

Contrary to the ^{11}B NMR results obtained with BMS, the signal due to the organoborane (in this case at 87.40 ppm) was easily identified. The boron signals due to the cage borons in the products, showed only minor changes in chemical shifts relative to those in the olefin. The results are summarized in Table 30. As can be seen, the signals in the products were resolved due to the symmetry of the molecule.

Table 30. ^{11} B NMR of Individual Signals and Differences for Individual Positions Relative to $BF_3 \cdot OEt_2$ in Benzene-d_6.

Compound	B(9)	B(12)	B(8,10)	B(4,5)	B(7,11)	B(3,6)
allyl-*o*-carborane	-2.30	-5.69	-9.20	-11.27	-13.28	-13.28
(B-R-9-BBN)	-2.29	-5.80	-9.38	-11.52	-13.31	-12.59
Δ[(alkene)-(B-R-9-BBN)]	+0.01	-0.01	-0.17	-0.25	-0.03	+0.70

Once again the signal due to B(12) (antipodal atom) was shown to be significantly relaxed.

The oxidation of the organoborane intermediates was carried out with sodium perborate at 25 °C for 12 h. Examination of the reaction products revealed 91% overall yield of alcohol and 9% of radical products, 5% of which consisted of propyl-*o*-carborane. The analysis was performed by ^{1}H NMR using a known amount of dibromobenzene as an internal standard. This analysis indicated 100% formation of 3-carboranyl-1-propanol. However, treatment of an aliquot of the crude products with BSTFA-1% TMSCl indicated, by GC/MS analysis, the presence of 1% of the secondary alcohol, thus establishing the boron distribution at the double bond as 99% terminal, 1% internal.

4.2.3 *Hydroboration of 1-Allyl-o-carborane with Chx_2BH in THF*

1-Allyl-*o*-carborane was hydroborated with (Chx_2BH) at 25 °C for 10 h. Oxidation of the resulting organoborane with sodium perborate indicated a boron distribution of 99:1 at the terminal and internal carbon atoms, respectively. The overall yield of alcohols, estimated by ^{1}H NMR using tetradecane as internal standard, was 96%. The isomeric ratio of alcohols was obtained by integration of the signals due to cage C-H protons of the two isomers, which resonated in acetone at 4.600 ppm (secondary) and 4.527 ppm (primary), respectively. The signal due to the methine proton in the secondary alcohol was obscured by the cyclohexanol byproduct Treatment with BSTFA, and analysis by GC/MS, indicated an identical ratio of isomeric alcohols to that determined by ^{1}H NMR. In this reaction, about 4% of

radical products were detected by GC/MS. The mass spectrum of the major radical product contained no $M^{+\cdot}$ ion. However, a base peak at 83 amu was observed which suggested a coupling product of the cyclohexyl group with the propyl carborane moiety.

4.2.4 *Hydroboration of 1-Allyl-2-hexyl-o-carborane with BH_3·THF.*

The hydroboration of 1-allyl-2-hexyl-*o*-carborane with BH_3·THF in THF (3:1 molar ratio) at 25 °C proceeded smoothly. Monitoring, by ^1H NMR, the rate of disappearance of the vinyl protons in the starting material revealed that the reaction was 46% complete in 40 min, 91% in 180 min, and 97% in 300 min. Monitoring by ^{11}B NMR spectroscopy revealed no signals downfield from BF_3·OEt_2. Two broad singlets were detected due to the cage boron atoms in the intermediates at -4.88(2) and -10.69(8) ppm. Examination of the ^{13}C NMR spectrum at the completion of the reaction revealed signals at 37.83 ppm (CH_2), 25.45 ppm (CH_2), and 24.94 ppm (CH_2B) due to the propyl side chain in the terminal boron addition product. Signals due to the internal boron intermediate were detected at 39.97 ppm (CH_2) and 14.75 (CH_3) ppm. These assignments were supported by a DEPT experiment. Finally, the signals due to the cage carbon atoms in the major isomer were detected at 80.05 ppm and 79.65 ppm. It appears that, upon conversion to products, the chemical shift difference of the cage carbon atoms is smaller ($\Delta\delta$ = 0.4), than that observed in the starting olefin ($\Delta\delta$ = 1.5). Oxidation of the organoborane intermediates with sodium perborate at 30 °C for 12 h yielded the primary and secondary alcohols in 91% total yield in a ratio of 67:33, respectively.

The GC/MS spectrum of the BSTFA-treated crude products indicated a ratio of primary to secondary alcohols of 68:32. The mass spectrum of the primary silyl ether showed a molecular ion cluster of peaks of high mass with a cut-off peak at 346 amu due to $M^{+\cdot}$-15, and an important ion peak at 103 amu due to the $CH_2{=}O^+$-$Si(CH_3)_3$ fragment. Similarly, the mass spectrum of the secondary silyl ether indicated a high mass cut-off peak at 346 amu and an ion peak of considerable intensity at 117 amu due to the $CH_3CH{=}O^+Si(CH_3)_3$ fragment. Only a trace amount (≈4%) of 1-propyl-2-hexyl-*o*-carborane was detected in the reaction. The remaining 5% of products were due to radical side reactions.

4.2.5 *The Hydroboration of 1-Allyl-2-hexyl-o-carborane with 9 BBN in THF.*

A solution of 1-allyl-2-hexyl-*o*-carborane in THF was treated with an equivalent amount of 9-BBN in THF and the reaction was sonicated at 40 °C for 12 h. Oxidation with sodium perborate yielded a product mixture with a boron distribution at the carbons γ- and ß- to the cage of 98:2, as determined by ^1H NMR integration. The total yield of alcohols was determined to be 90% by ^1H NMR, using a dibromobenzene as a standard. A small amount (5%) of coupling products with THF was detected.

4.2.6 *Hydroboration of 1-Allyl-2-hexyl-o-carborane with Chx_2BH in THF.*

Hydroboration of 1-allyl-2-hexyl-*o*-carborane, with dicyclohexylborane (1:1 molar ratio) at 25 °C for 12 h proceeded to the trialkylborane stage as evidenced by the appearance of a signal at δ 84 in the ^{11}B NMR spectrum. Signals due to the cage

borons were detected at -5.17 ppm (2) and -10.96 ppm (8). The ^{13}C NMR spectrum contained signals due to the terminal boron intermediate at 38.96 ppm (CH_2), 25.65 ppm (CH_2), and 25.13 ppm (CH_2B). The carbon atom signals due to the cyclohexyl group in the intermediate were detected at 36.61 ppm (BCH), 28.40 ppm (CH_2), 28.19 ppm (CH_2), and 27.95 ppm (CH_2). These assignments were based on a DEPT experiment. The signals due to the cage carbon atoms at 81.25 and 81.13 ppm nearly overlapped . This represents a difference, $\Delta\delta$, of 0.12. Comparison of this value with those noted earlier indicates that the δ values of the cage carbons are sensitive to the alkyl substituents in the side chains.

Oxidation with sodium perborate afforded a 90% yield of carborane alcohols. Analysis of the alcohols by GC/MS after derivatization with BSTFA indicated that the original boron distribution was 98.5% primary and 1.5% secondary. Similarly, ^1H NMR integration of the C-H protons α to the OH groups at δ 3.67 and 4.15 indicated a ratio of 98:2. No radical products were detected in this reaction.

4.2.7 *Hydroboration of 1-Crotyl-o-carborane with BH_3·THF.*

A 15:85 *cis*:*trans* mixture of crotyl-*o*-carborane was hydroborated with BH_3·THF at 25 °C (3:1 molar ratio). Monitoring, by ^1H NMR, the disappearance of the cage C-H proton in the olefin at δ 3.389 indicated that the reaction was 80% complete in 3 h and 100% complete in 12 h. The *cis* olefin hydroborated much faster than the *trans*; its reaction was complete within 2 h. The ^{11}B NMR spectrum revealed no signals due to exopolydehral boron atoms. Signals due to the cage boron atoms were detected at δ -2.80 (1), -6.13 (1), -9.69 (2), and -11.60 (6). Monitoring

the reaction by ^{1}H NMR and ^{13}C NMR indicated a complex reaction. This was not unexpected, however, in light of the sluggishness of the *trans* hydroboration reaction and the non-isomeric purity of the starting material.

Oxidation of the hydroboration products by alkaline hydrogen peroxide afforded alcohols in 92% yield. The yield was established by ^{1}H NMR using a known amount of dibromobenzene as an internal standard. The ratio of the ß- and γ-alcohols was determined to be 91:9. This was calculated by integration of the methyl signals in the alcohols at 0.852 ppm (triplet) and 1.091 ppm (doublet). Examination of the ^{11}B NMR spectrum of the crude products indicated the present of ~3% cage degradation products in the organic phase. Since the methine protons α- to the hydroxyl groups in the isomeric alcohols were not independently resolved, the structural identity of these products was further examined using C/H COSY and H/H COSY experiments. The H/H COSY spectrum of the crude products is shown in Figure 16. The entry point in this spectrum is the methine proton signals at δ 3.645 ppm from which the signals at δ 2.368 and δ 1.406 are reached. This latter signal is connected by cross peaks with the triplet at δ 0.852. The atoms identified are consistent with the structural formula $RCH_2CH(OH)CH_2CH_3$ (R=cage) due to the ß-alcohol. Similarly, the signal at δ 3.645 is connected through a weak coupling with the doublet at δ 1.091. A similar weak coupling is observed between a multiplet at ~1.624 ppm and the signal at δ 2.368. Thus the latter signals are consistent with those in the γ-alcohol, $RCH_2CH_2CH(CH_3)OH$. Finally, the results of the C/H COSY experiment are shown in Figure 17. As can be seen, only the signals due to

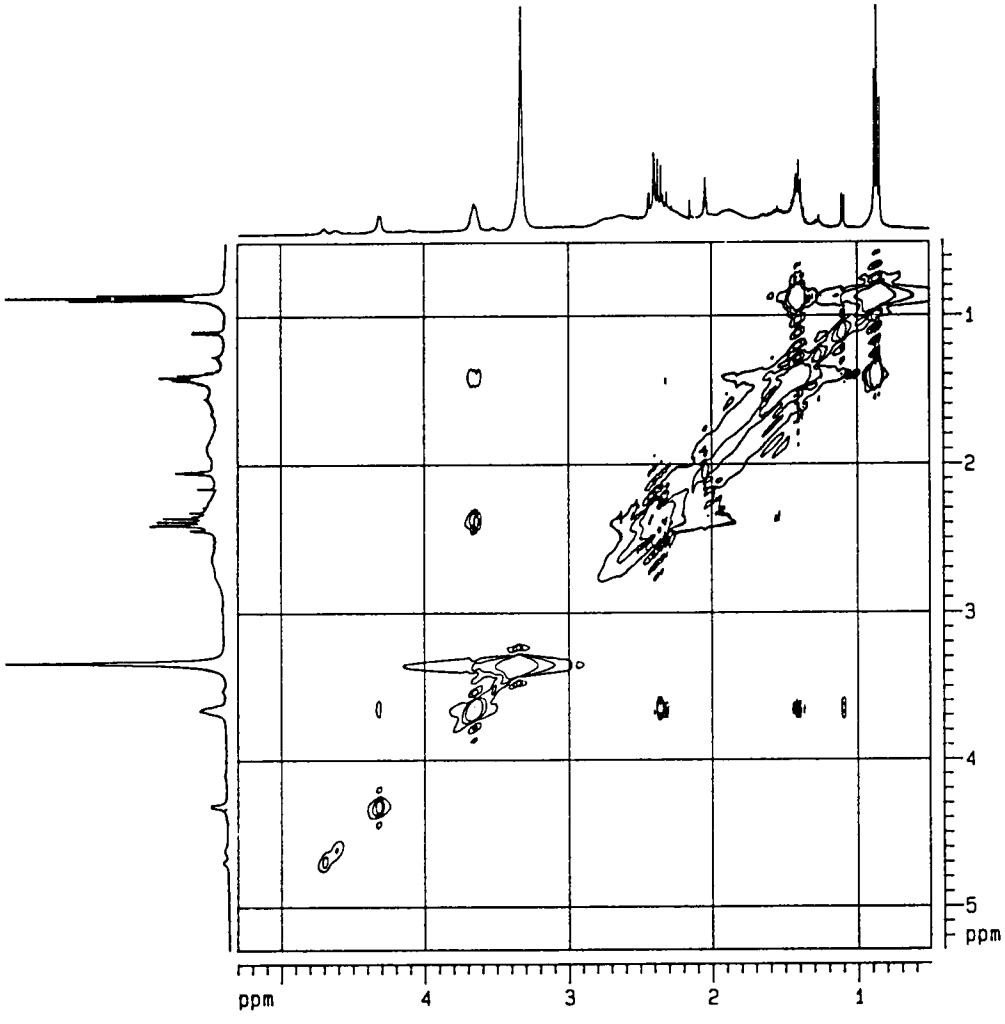


Figure 16. H/H COSY NMR spectrum of the Products in the reaction of 1-Crotyl-*o*-carborane with BH_3·THF (3 : 1 molar ratio).

the major isomer were detected. The chemical shift values are tabulated in Table 31.

Table 31. Chemical Shift Values of C/H COSY of 1-*o*-Carboranyl-2-butanol

δ_{C13}	δ_{H1}	Assignment
71.93	3.654	C(H)OH
44.53	2.368	CH_2
31.34	1.407	CH_2
9.90	0.852	CH_3

The GC/MS spectrum of the oxidized products after treatment with BSTFA-1% TMSCl was in full agreement with the regioisomer ratio of the alcohols as well as the structural assignment determined by ^{1}H NMR. The distribution of alcohols was established to be 91% ß and 9% γ. The mass spectrum of the silyl derivative of the ß-alcohol showed an ion fragment at 131 amu due to $(CH_3)_3SiO^+=CHCH_2CH_3$ whereas the γ- silyl derivative showed a similar peak at 117 amu due to the $(CH_3)_3SiO^+=CHCH_3$ fragment ion. These ion fragments clearly established the structures of the alcohols. It is interesting to point out that the silyl derivative of the ß-alcohol had an earlier GC elution time than the γ-derivative.

4.2.8 *Hydroboration of 1-Crotyl-o-carborane with 9-BBN in Hexanes.*

The hydroboration of crotyl-*o*-carborane with 9-BBN in hexanes (1:1 molar ratio) was accomplished using ultrasound at 45 °C for 9 h. Monitoring the reaction by ^{11}B NMR spectroscopy indicated the disappearance of the signal due to 9-BBN dimer at δ 27.5 with the concomitant formation of a signal at δ 87.7. The

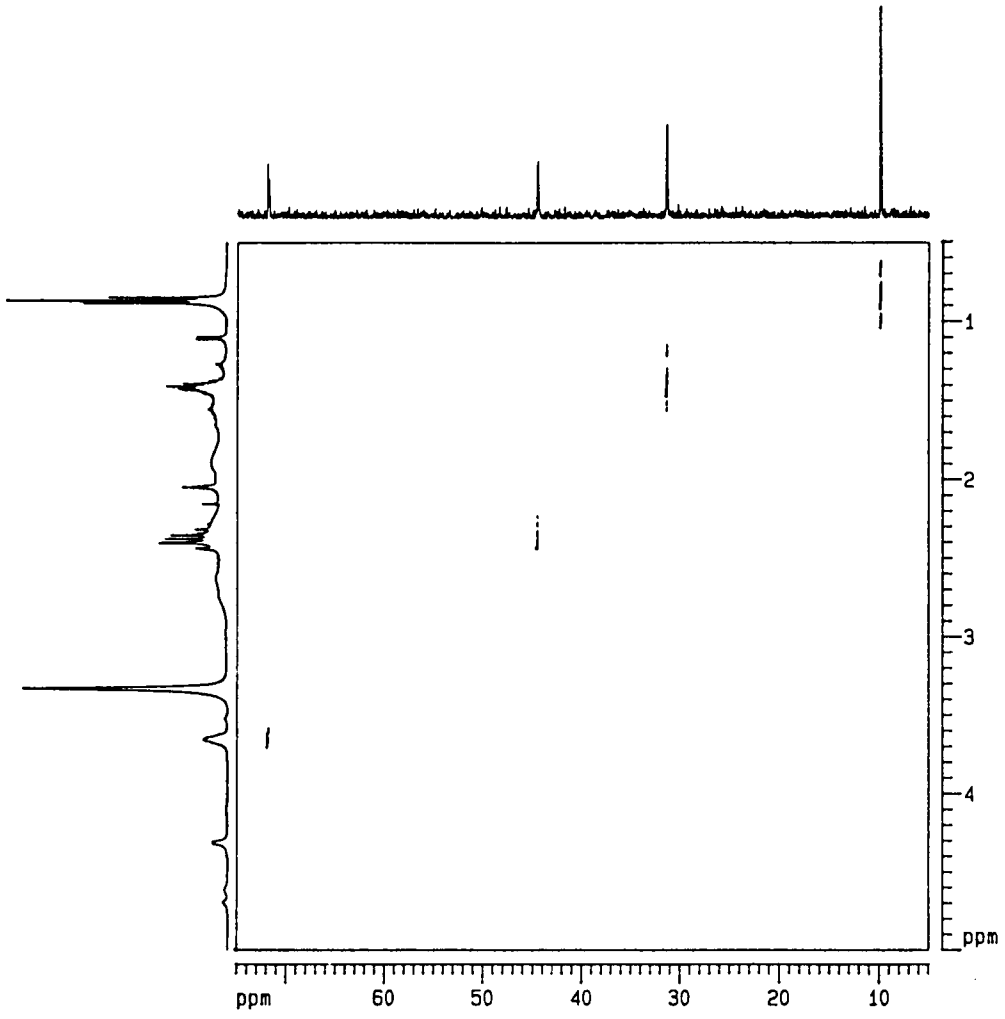


Figure 17. C/H COSY NMR spectrum of the products in the reaction of 1-crotyl-*o*-carborane with BH_3·THF (3 : 1 molar ratio).

boron atoms due to the cage in the hydroboration products resonated at δ -1.87 (1), -5.04 (1), -8.92 (2), -10.83 (2), -11.82 (2), and -12.89 (2), respectively. Oxidation of the reaction mixture with alkaline hydrogen peroxide yielded ß- and γ-alcohols in 87% yield, as determined by ^{1}H NMR using dibromobenzene as the internal standard. The isomeric ratio of the ß- and γ-alcohols was determined by ^{1}H NMR to be 93:7.

4.3 *Discussion*

In the reaction of BH_3·THF with 1-allyl-*o*-carborane, 64-65% of the boron adds to the terminal carbon and 34-36% adds to the internal carbon. The considerable degree of boron addition to the internal carbon of the double bond must be the result of the strong electronic effects exerted by the carboranyl group. The steric effect of the cage is not expected to play an important role in the regioselectivity of the hydroboration reaction with 1-allyl and 1-allyl-2-hexyl-*o*-carboranes. In the reaction of borane with allylbenzene, 10% of the boron adds to the position nearer to the ring, indicating that the substituent exerts an electronic influence on the direction of addition. Larger directing effects for the internal position have been observed; they vary from 19% in the allyl ethyl ether to 45% in the allyl tosylate (Chart 9, Chapter I, pg.15). In the reaction of allyl chloride and allyl acetate with BMS, both substituents exert a powerful directive effect causing 40% and 35% of the boron to become attached to the secondary position. Comparison of the results obtained using **4** with those using allyl chloride demonstrates that both groups exhibit similar directive effects. However, better agreement is observed with the acetate substituent. Despite the similarity in the

direction of boron addition with these groups, the carborane substituent gives rise to organoborane intermediates of considerably different reactivity. Thus, whereas the internal boron derivatives from allyl chloride and allyl acetate undergo a spontaneous elimination to propylene during hydroboration, the carborane substituted allyl derivatives survive both hydroboration and base catalyzed elimination at 25 °C and 30 °C.

Comparison by GC of the ratios of primary to secondary alcohols, obtained by oxidizing the hydroboration products from 1-allyl-2-hexyl-*o*-carborane and 1-allyl-*o*-carborane indicates a 2% increase in regioselectivity for the primary alcohol (67% vs 65% terminal) as the substituent in C(1) of the o-carborane nucleus varies in the order $H < C_6H_{13}$. This is in accord with previous studies which found that electron-donor substituents on the C(1) atom of the *o*-carborane cage lower the electron acceptor effect of the *o*-carboranyl group and, thus, the amount of boron addition to the internal position of the double bond.

In the hydroboration of 1-allyl-2-hexyl-*o*-carborane and 1-allyl-*o*-carborane, a common side product was the corresponding propyl carboranes in quantities varying from 3-10%. The structure of this product was confirmed by an independent synthesis of 1-propyl-*o*-carborane by hydrogenation of 1-allyl-*o*-carborane. Examination by ^{13}C NMR of the organoborane intermediate obtained in the reaction of 1-allyl-*o*-carborane with borane, indicated that it is stable towards hydrolysis, since addition of H_2O or D_2O failed to produce 1-propyl-*o*-carborane. Similar results were also obtained in base. Thus the formation of propyl-*o*-carborane is believed to be

due to radical side reactions during oxidation which are more prevalent with alkaline hydrogen peroxide. In this regard it should be pointed out that Bigley and co-workers (160) detected 10% of radical products in the hydroboration-oxidation of 1-hexene when alkaline hydrogen peroxide was employed as an oxidizing agent.

The employment of Chx_2BH and 9-BBN as hydroborating agents resulted once again in the reversal of the regioselectivity, directing ≥98% of boron to the terminal position.

The crotyl system with its internal double bond provided a test of the electronic effect of the *o*-carboranyl group. As compared to the allyl system, there was observed a marked enhancement in the addition of the boron at the position closer to the carborane. Thus, in a reaction with BH_3·THF, a 91% ß- and 9% γ-addition of boron was obtained as compared to a 34% ß, 66% γ distribution realized with 1-allyl-*o*-carborane. The regioselectivities observed with some representative crotyl systems (Chart 10, Chapter I, pg.16) in the reaction with BMS were as follows: crotyl chloride, 100% ß; crotyl acetate, 95% ß; crotyl benzyl ether, 91% ß; crotyl alcohol 90% ß; crotyl phenyl ether, 86% ß; and crotyl ethyl ether, 84% ß. In this case, the directive effect of the carboranyl group was similar to that of the hydroxy and the benzyl ether groups. Even though 9-BBN is more bulky than BH_3·THF, it exhibited a 93% selectivity for the ß- position as compared to 91% with the latter.

CHAPTER V

Hydroboration of C(1)-Alkenyl Derivatives of *o*-Carborane Carrying a Distant Double Bond.

5.1 *Introduction*

In the hydroboration of representative homoallyl derivatives it has been shown that the substituents exhibit a diminished but still noticable directive effect. As was observed previously, the percent of boron adding to the internal carbon atom of the vinyl group increases with electronegativity: 1-butene, 6%; homoallyl methyl ether, 11%; homoallyl alcohol, 14%; and homoallyl chloride, 16%. When the double bond is positioned further than three CH_2 units from the substituent, however, the hydroboration reaction proceeds to place 94% of boron on the terminal carbon regardless of the substituent.

In this chapter, the directive influence of the *ortho* carboranyl moiety, located distant from the double bond, is explored in the hydroboration of the following representative olefins: 1-homoallyl-*o*-carborane, 1-homoallyl-2-methyl-*o*-carborane, 1-(4-pentenyl)-*o*-carborane, and 1-(7-octenyl)-*o*-carborane. The representative hydroborating agents used in this study were BH_3·THF, Chx_2BH, and 9-BBN.

5.2 *Results*

5.2.1 *Hydroboration of 1-Homoallyl-o-carborane with BH_3·THF*

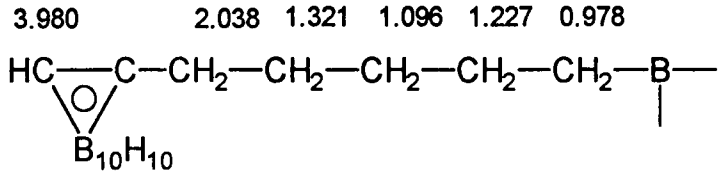
Homoallyl-*o*-carborane was hydroborated with BH_3·THF (3:1 molar ratio) at 25 °C. Examination of the product by ^{11}B NMR indicated a weak signal at δ 79.4

due to the exopolyhedral boron in the intermediate. The cage borons resonated at δ -1.79 (1), -4.98 (1), -8.56 (2), -10.51 (4), -11.99 (2). Contrary to the complexity of the organoborane intermediates produced in the previous systems, a straighforward reaction was indicated. In the ^{1}H NMR spectrum, four envelopes of multiplet peaks were detected at δ 2.194, 1.365, 1.178, and 0.799 due to the terminal boron intermediates. A doublet due to the methyl group of an intermediate with boron attached internally was detected at δ 0.827. The results of a H/C COSY NMR experiment of the major tributylcarboranylborane intermediate are summarized in Table 32.

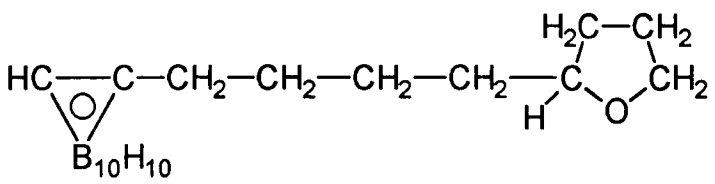
Table 32. ^{13}C and H/C COSY Data of Tributylcarboranylborane in THF-d_8.

δ_{C13}	δ_{H1}	Assignment
76.97	-	CR (cage)
62.90	4.325	CH (cage)
38.58	2.194	CH_2
32.99	1.413	CH_2
24.36	1.208	CH_2
20.31	0.792	CH_2-B

In the ^{13}C NMR spectrum, the signal at 20.31 ppm was considerably broadened and it was assigned to the methylene carbon α to the exopolyhedral boron. The proton connectivities in this intermediate were examined by a H/H COSY experiment, the results of which are summarized below.



The oxidation of the hydroboration products with alkaline hydrogen peroxide afforded carborane products in 95% yield, as evidenced by ^{1}H NMR analysis using dibromobenzene as an internal standard. The yield of the alcohols, however, was only 75%. Large amounts of 1-butyl-*o*-carborane (10%), and of coupling products between THF and butyl-*o*-carborane (15%) were also detected. The distribution of boron between the terminal and internal carbon atoms of the original double bond was shown to be 93% terminal and 7% internal. The ratio determined by GC/MS after treatment of the alcohols with BSTFA was 91:9. The large quantity of the protonolysis product was also supported by GC/MS data. The mass peak due to this product showed a molecular ion cluster with a high mass cut-off peak at 202 amu and a base peak at 43 amu. A partially purified sample of the proposed THF adduct was isolated by column chromatography (SiO_2/hexanes). ^{1}H NMR analysis revealed the following resonances: δ 3.54 (1H, s) due to a cage C-H group, δ 3.81 (1H, m) and δ 3.68 (2H, m) due to protons adjacent to an oxygen atom, δ 2.18 (2H) due to a CH_2 group attached to a carborane cage, and δ 1.94-1.85 (6H, m) due to three CH_2 groups. Unfortunately the region of the spectrum between δ 1.6 to 1.2 was obscured by impurities and the remaining resonances could be not detected. These results provide support for a structure in which the furanyl group is attached to the alkyl side chain. A structure which is consistent with the above data is presented below.



The mass spectrum of this compound did not contain peaks due to the molecular ion. The highest mass cluster of peaks had a high mass cut-off peak at 201 amu. The base peak in the spectrum was at 71 amu and was due to the furanyl fragment. Both fragment ions detected were consistent with the expected fragmentation of the proposed compound.

In a separate experiment, the oxidation was performed with sodium perborate in a D_2O/THF mixture to afford a 95% yield of carborane products, which by ^1H NMR analysis revealed the following products; alcohols (75%), 1-butyl-*o*-carborane (6%), and radical products (19%). The ratio of primary to secondary alcohols was 93:7. D_2O was used as a co-solvent in the oxidation with sodium perborate in an effort to obtain evidence of an ionic pathway leading to the butyl-*o*-carborane. The mass spectrum of the product, however, showed the incorporation of one deuterium in the compound instead of the desired two. The mass spectrum showed a molecular ion cluster of peaks with a high mass cut-off peak at 203 amu and a maximum intensity peak at 200 amu as opposed to 202 and 199, respectively, obtained for the undeuterated species. It was deduced that deuterium incorporation had occurred on the cage since no deuterium was noted in any of the alkyl fragments obtained.

The mass spectrum of the primary alcohol revealed a molecular ion cluster with a high mass cut-off peak at 219 amu and a base peak at 31 amu. The secondary alcohol showed a similar molecular ion cluster of peaks and a base peak at 45 amu. Upon treatment of the alcohols with BSTFA, both silyl derivatives showed a high mass cluster of peaks with a high mass cut-off peak at 275 amu due to the loss of

CH_3 from the molecular ion. The silyl derivative of the primary alcohol had a base peak at 103 amu, whereas the secondary alcohol derivative had a base peak at 117 amu. The ratio of the primary to secondary alcohols was shown by GC/MS to be 91:9.

5.2.2 *Hydroboration of 1-Homoallyl-o-carborane with Chx_2BH.*

The hydroboration-oxidation of homoallyl-*o*-carborane with dicyclohexyl borane (Chx_2BH) proceeded smoothly. The olefin was hydroborated with Chx_2BH (1:1 molar ratio) at 25 °C for 12 h followed by oxidation with sodium perborate, to afford the carborane alcohols in 91% as evidenced by ^1H NMR spectroscopy. GC/MS analysis indicated coupling by-products of the cyclohexyl group and butyl-*o*-carborane (≤5%). The molecular ion cluster of this compound had a high mass cut-off peak at 284 amu and a base peak at 83 amu. The distribution of boron was determined by treating an aliquot of the crude products with BSTFA, by GC/MS analysis. The boron was attached primarily to the primary carbon (≥99%).

5.2.3 *Hydroboration of 1-Homoallyl-2-methyl-o-carborane with BH_3·THF.*

The 1-homoallyl-2-methyl-*o*-carborane was hydroborated with BH_3·THF in THF (3:1 molar ratio) for 3 h at 25 °C. The ^{11}B NMR spectrum of the hydroboration products, however, did not contain a signal due to the trialkylborane intermediate. In the cage boron region of the spectrum, the NMR revealed a substantial reduction in the intensity of the signal due to the boron atom B(12) antipodal to the exopolydehdral boron. This relaxation effect was observed for most of the B(12) cage borons of the carboranes in this study. Oxidation with sodium

perborate gave carborane species in 90% yield. This was determined by ^{1}H NMR integration of the cage methyl signals in the products using dibromobenzene as an internal standard. The distribution of products was as follows: 4-methylcarboranyl-1-butanol, 73%; 4-methylcarborany-2-butanol, 5%; 4-methylcarboranylbutane, 12%; and methylcarboranylbutane·THF adducts, 10%. A ratio of primary to secondary alcohols of 93:7 was obtained. When the alcohols were treated with BSTFA, and the resulting silanes examined by GC/MS, the ratio was found to be 91 (primary) to 9 (secondary). The proposed THF adduct was isolated by HPLC and characterized by ^{13}C NMR. The ^{13}C NMR spectrum contained resonances at δ 78.91 (CH), 78.25 (Cage C), 74.76 (Cage C), 67.8 (CH_2), 35.38 (CH_2), 35.28 (CH_2), 31.55 (CH_2), 29.73 (CH_2), 26.16 (CH_2), 25.78 (CH_2), and 23.19 (CH_3). These resonances were in agreement with those expected for a radical coupling product containing the 1-butyl-2-methyl-*o*-carborane and the furanyl group.

5.2.4 *Hydroboration of 1-Homoallyl-2-methyl-o-carborane with Chx_2BH in THF.*

The hydroboration of 1-homoallyl-2-methyl-*o*-carborane with Chx_2BH in THF (1:1 molar ratio, 12 h) proceeded in such a manner that 100% of the boron was attached to the terminal carbon atom of the original double bond. Oxidation of the reaction mixture was performed with sodium perborate in a glove bag and afforded, after workup, primary alcohol in 89% yield. The remaining products were due to THF·carborane adduct (9%) and 4-methylcarboranylbutane (2%). In a separate experiment, in which the addition of sodium perborate was done at the bench top under a blanket of nitrogen the yields of the side reactions increased considerably as

evidenced by ^{1}H NMR analysis. Under these conditions, 4-methylcarboranylbutane (14%) as well as furanyl (6%) and cyclohexyl (6%) coupling products were formed. The total yield of products in the reaction was 94%.

The mass spectrum of the suspected cyclohexyl adduct contained a molecular ion cluster with a high mass cut-off peak at 298 amu and base peak at 83 amu. The ratio of the isomeric alcohols was established by GC/MS after treatment with BSTFA. They were found to be > 99% primary. The mass spectrum of this compound showed a molecular ion peak at 290 amu, ($M^{+\cdot}$-CH_3), a base peak at 75 amu, and the key fragment for primary silated alcohols at 103 amu.

5.2.5 *Hydroboration of 1-(4-Pentenyl)-o-carborane with BH_3·THF.*

Hydroboration of 1-(4-Pentenyl)-*o*-carborane with BH_3·THF, at 25 °C (3:1 molar ratio), proceeded rapidly to the trialkylborane stage. The disappearance of the vinyl protons in the starting material, as evidenced by ^{1}H NMR analysis, indicated that the reaction was 92% complete in 26 min, 95% in 35 min, 97% in 54 min, and 100% complete in 120 min. The ^{11}B NMR spectrum revealed the presence of a weak broad signal at δ 79.4 due to the exopolydral boron in the products. The signals due to the cage borons were detected at δ -2.94(1), -6.19(1), -9.74(2), and -11.75(6). The ^{1}H NMR spectrum indicated clean formation of the trialkylborane intermediates. All of the signals observed were due to the terminal boron isomer except for a doublet at δ 0.710 which was due to the methyl group present in the secondary isomer. This signal accounted for 7% of the products. The C/H COSY spectrum of the major hydroboration product is shown in Figure 18. The

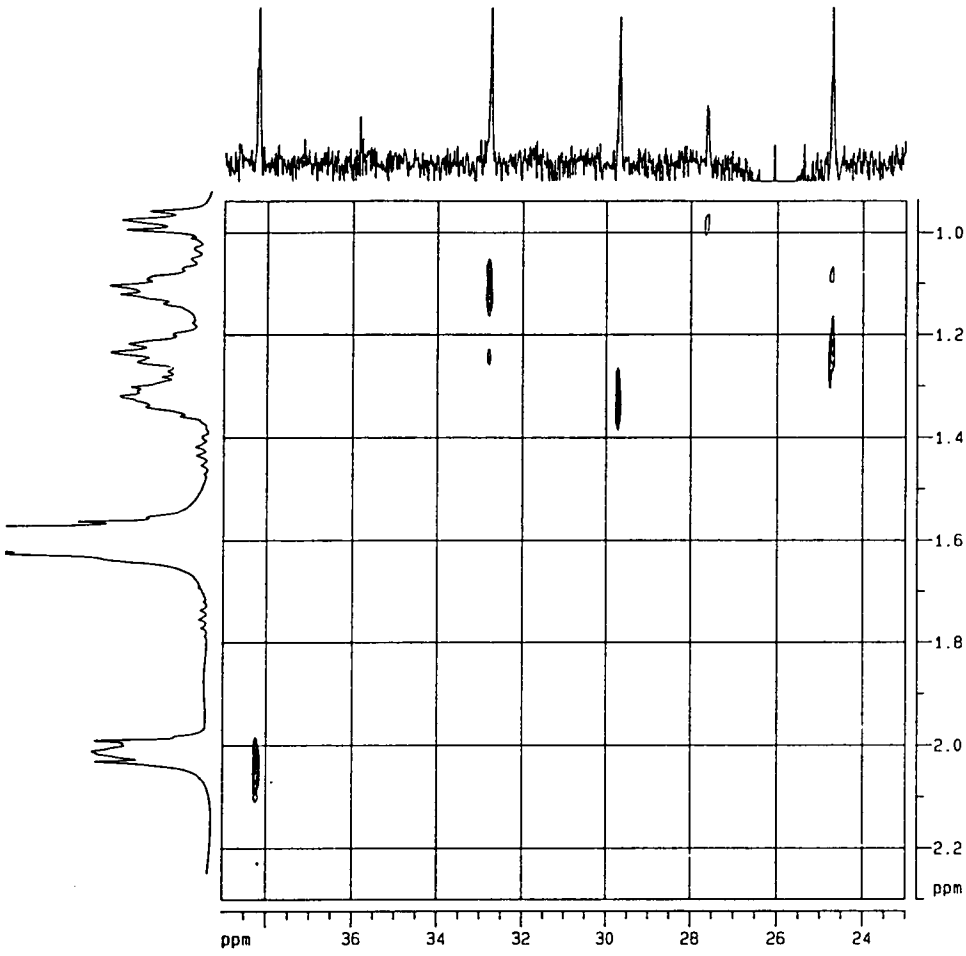


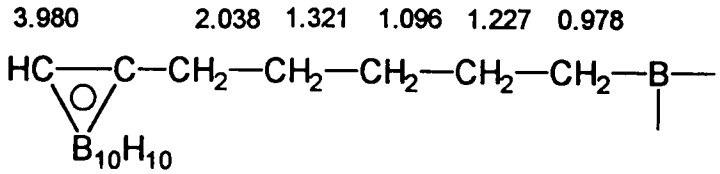
Figure 18. C/H COSY NMR spectrum of the intermediates in the reaction of 1-(4-pentenyl)-*o*-carborane with BH_3·THF (3 : 1 molar ratio).

NMR data are summarized in Table 33. The assignments of resonances were established by a DEPT experiment. Not shown in Table 33 were the ^{13}C signals of the minor secondary isomer at δ 76.93, 63.01, 38.64, 32.96, 24.99, and 14.56. The BCH carbon signal was not detected due to it low intensity.

Table 33. ^{13}C NMR and C/H COSY DATA of Tripentylcarboranylborane in THF-(C_6D_6).

δ_{C13}	δ_{H1}	Assignment
76.35	3.988	Cage CR
62.25	2.042	Cage CH
38.19	2.042	CH_2
32.66	1.097	CH_2
29.60	1.321	CH_2
27.60	0.978	CH_2B
24.61	1.231	CH_2

The H/H COSY spectrum of the tripentylcarboranyl borane is shown in Figure 19. The results of this experiment are summarized below.



Oxidation of the organoborane intermediates with sodium perborate afforded a 92% yield of alcohols in the ratio of 95 (primary): 5 (secondary), as evidenced by ^1H NMR analysis. Trace amounts of 1-pentyl-*o*-carborane (2%) and cage degradation products (2%) were also detected by ^1H and ^{11}B NMR. The GC/MS spectrum of the silated crude product (BSTFA) revealed a ratio of 5-*o*-carboranyl-1-

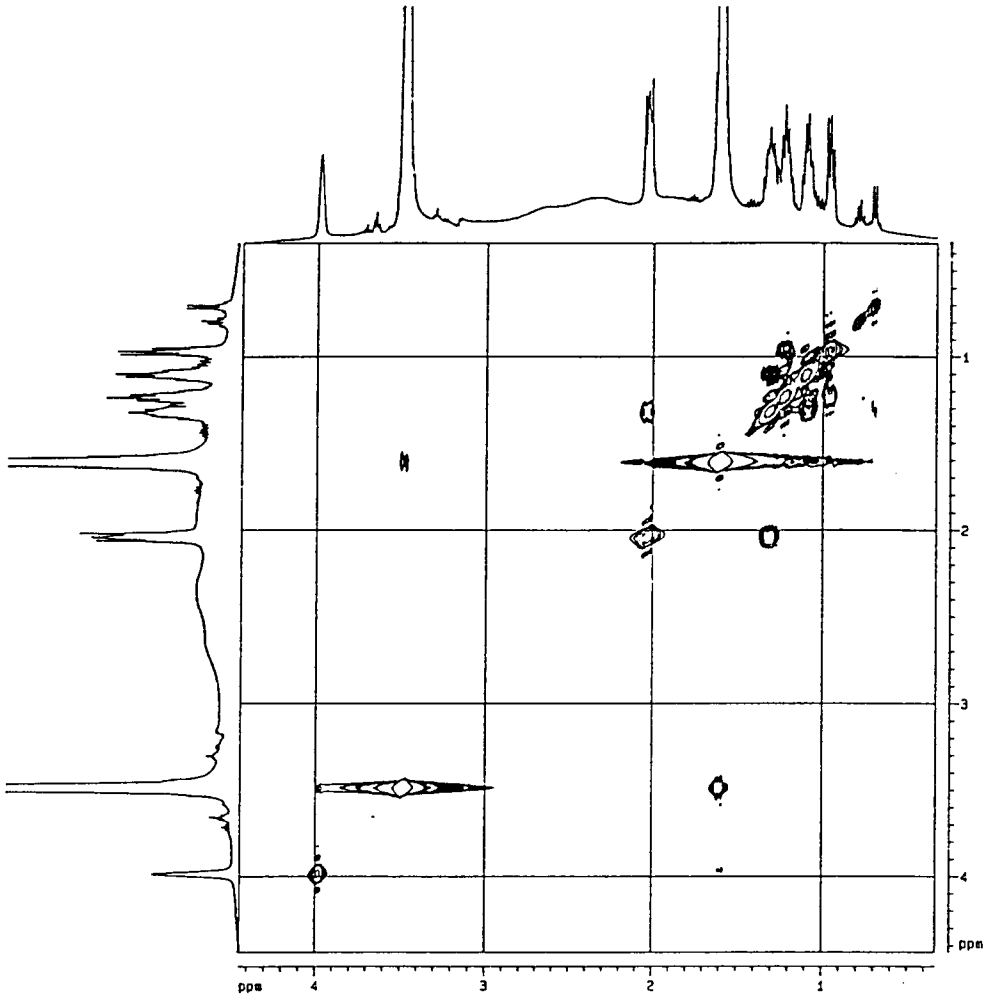


Figure 19. H/H COSY NMR spectrum of the intermediates in the reaction of 1-(4-pentenyl)-*o*-carborane with BH_3·THF (3 : 1 molar ratio).

pentanol and 5-*o*-carboranyl-2-pentanol of 94:6. In a separate experiment, the oxidation of the trialkylboranes with an equivalent amount of alkaline hydrogen peroxide under an inert atmosphere for 12 h at 27 °C afforded a 97% yield of carborane products. Examination of the product mixture by ^{1}H NMR gave the following: 1-pentyl-*o*-carborane (23%), 5-*o*-carboranyl-1-pentanol (59%), 5-*o*-carboranyl-2-pentanol (3%), a furanyl pentylcarborane adduct (8%), and additional side products (7%). Examination of the product mixture by ^{13}C NMR spectroscopy indicated that the major products of the reaction were the primary alcohol and the protonolysis product. The latter was isolated by HPLC analysis, and it was characterized by ^{13}C, and ^{1}H NMR spectroscopies. In another experiment, in which a threefold excess of alkaline hydrogen peroxide was employed as an oxidizing agent, ^{1}H NMR analysis of the product mixture gave the following results: 1-pentyl-*o*-carborane (13%), 5-*o*-carboranyl-1-pentanol (82%), and 5-*o*-carboranyl-2-pentanol (5%). No furanyl adducts were detected. These results suggest that when alkaline hydrogen peroxide is employed in equivalent amounts, higher yields of radical products accompanied the formation of alcohols. This is possibly due to competing side reactions or incomplete oxidation products. Employment of excess oxidizing agent resulted in higher yields of alcohols. The method of choice, however, appeared to be oxidation with sodium perborate. Since the carborane cage was shown by ^{11}B NMR to be stable in the presence of up to 300% excess oxidizing agent in a 1:1 THF/H_2O mixture for 10 h at 40 °C (only ~3-4% *nido* detected), 50-100% excess oxidizing agent was general employed in order to ensure complete oxidation.

5.2.6 *Hydroboration of 1-(4-Pentenyl)-o-carborane with 9-BBN in Hexane.*

1-(4-Pentenyl)-*o*-carborane was hydroborated with a solution of 9-BBN in hexanes at 40 °C under ultrasound. Monitoring the reaction by ^{11}B NMR revealed the appearance of a signal at δ 87.2 due to the trialkylborane intermediate (B-R-9-BBN) and showed that the reaction was complete in 2 h. The boron signals due to the cage atoms were detected at δ -2.66 (1), -6.04 (1), -9.60 (2), -11.75 (4), and -12.45 (2). A summary of the data observed in the H/C COSY spectrum is given in Table 34.

Table 34. H/C COSY NMR Data of the Reaction of 1-(4-Pentenyl)-*o*-carborane with 9-BBN (Hexanes/C_6D_6).

δ_{C13}	δ_{H1}	Assignment
75.71	-	Cage CR
61.43	2.96	Cage CH
38.12	1.95	CH_2
33.50	2.08	CH_2(9-BBN)
32.38	1.13	CH_2
31.47	1.90	BCH (9-BBN)
29.40	1.23	CH_2
28.18	-	BCH_2
23.34	1.52	CH_2
23.62	1.45	CH_2 (9-BBN)

As can be seen, the signals are in accord with those predicted for the B-R-9-BBN intermediate although, the signals due to BCH_2 protons were not observed in the ^1H projection. The corresponding signal in the ^{13}C projection was assigned to 28.18 ppm due to its broad nature and low intensity.

Oxidation with alkaline hydrogen peroxide afforded exclusively the primary

alcohol in 89% yield, as evidenced by ^{1}H NMR analysis using a known amount of dibromobenzene as an internal standard. In addition to the alcohol, 1-pentyl-*o*-carborane (8%) was also detected. After oxidation, analysis by ^{11}B NMR of both the organic and aqueous phases indicated trace amounts of cage degradation products.

5.2.7 *Hydroboration of 1-(7-Octenyl)-o-carborane with BH_3·THF*

Hydroboration of 1-(7-Octenyl)-*o*-carboranebenzene in benzene with BH_3·THF (3:1 molar ratio) proceeded cleanly to the trialkylborane, as evidenced by the complete consumption of olefin. Monitoring the reaction by ^{1}H NMR spectroscopy at 25 °C by following the disappearance of the vinyl protons indicated that the reaction was 89% complete in 2 h and nearly 100% complete at 4 h. Examination of the product mixture by ^{11}B NMR spectroscopy revealed a broad signal at δ 85 due to the formation of the corresponding trialkylborane. The signals due to the boron atoms (B (3,6), B (4,5), and B (7,11)) of the cage in the organoborane broadened and coalesced at δ -12.45. The remaining boron signals remained unchanged. The ^{1}H NMR spectrum of the trialkylborane intermediate also indicated a smooth hydroboration reaction. The H/C COSY spectrum of the hydroboration products is shown in Figure 20. A tabulation of these signals is presented in Table 35.

In addition to the ^{13}C and ^{1}H resonances shown in Table 35, the ^{13}C NMR spectrum also had signals at δ 76.22 and δ 28.25 due to the substituted carbon atom of the cage, and the methylene carbon α to the exopolyhedral boron, respectively. Oxidation with excess H_2O_2/OH^- afforded the isomeric alcohols in 93%

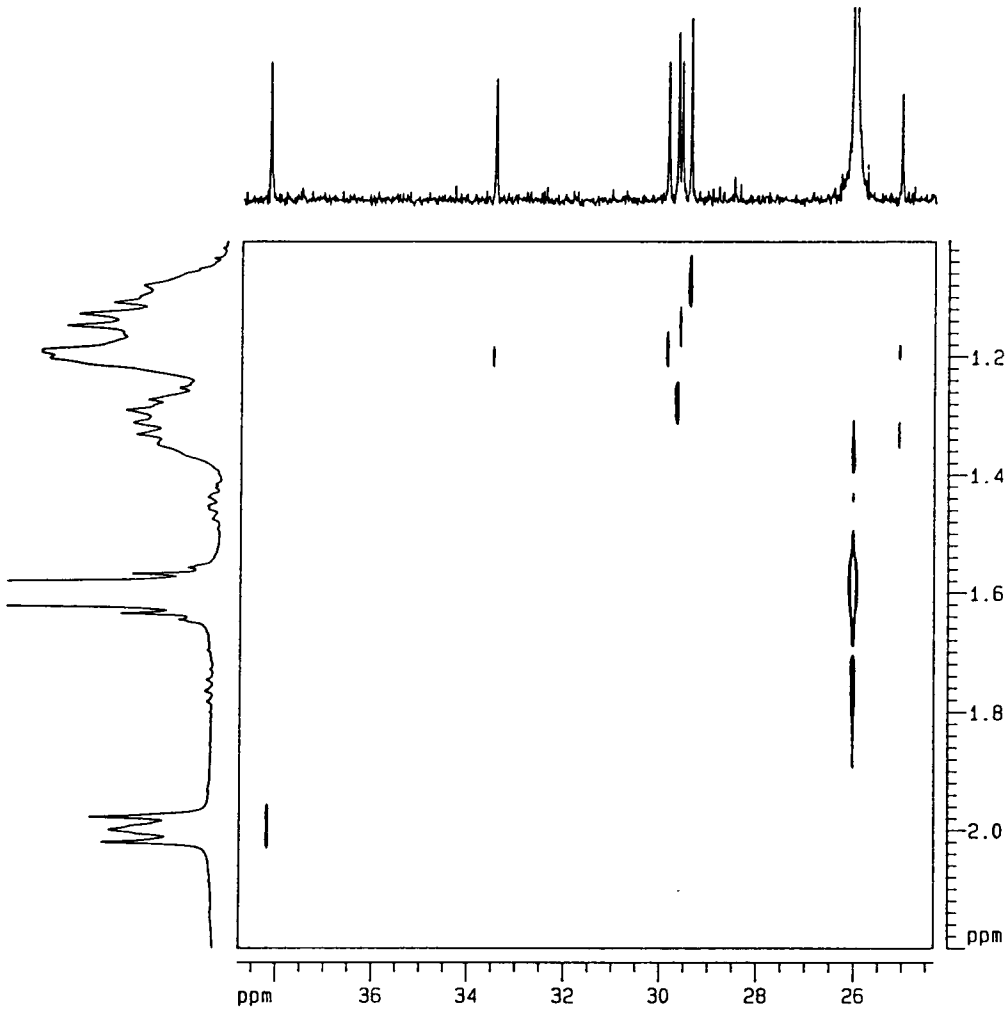


Figure 20. C/H COSY NMR spectrum of the intermediates in the reaction of 1-(7-octenyl)-*o*-carborane with BH_3·THF (3 : 1 molar ratio).

Table 35. Tabulation of the H/C COSY Data of the Reaction of 1-(7-Octenyl)-*o*-carborane with BH_3·THF in Benzene.

δ_{C13}	δ_H
62.13	3.791
38.18	1.990
33.44	1.194
29.85	1.181
29.65	1.271
29.57	1.135
29.38	1.078
25.02	1.331

yield, as evidenced by ^{1}H NMR analysis. 1-Octyl-*o*-carborane, a protonolysis product, was also detected in 5% yield. The ratio of alcohols was found to be 94:6 primary:secondary. The ^{11}B NMR spectrum of the organic phase following work-up indicated ~4% of cage degradation products. No such products were observed in the aqueous phase. The GC/MS spectrum of the BSTFA derivative of the alcohols indicated a distribution of 95% primary alcohol and 5% of the secondary. The mass spectrum of the primary silyl ether showed a cluster ion with a high mass cut-off peak at 333 amu ($M^{+\cdot}$-15) and a base peak at 103 amu. The secondary silyl ether showed identical high mass peaks and a base peak at 117 amu. These values are consistent with the postulated assignments of these compounds.

5.2.8 *Hydroboration of 1-(7-Octenyl)-o-carborane with 9BBN in Hexanes.*

Hydroboration of 1-(7-Octenyl)-*o*-carborane, with 9-BBN using ultrasound at 40 °C proceeded cleanly to afford the corresponding trialkylborane which, upon oxidation with sodium perborate, yielded the terminal alcohol, exclusively, in a 92% yield. A small amount of 1-octyl-*o*-carborane (3%) was also obtained.

Monitoring of the reaction by ^{11}B NMR spectroscopy over time, showed that the signal due to 9-BBN dimer at 28.1 ppm disappeared with the concomitant formation of a singlet at 88.4 ppm. The reaction was shown to be nearly 100% complete within 2 h. In the high field region of the ^{11}B NMR spectrum, the resonances due to the cage boron atoms were clearly resolved into five singlets at δ -1.77 B (9), -5.32 B (12), -8.86 B (8,10), -11.04 B (3,6) -12.08 B (4,5) and -12.84 B (7,11). GC/MS analysis of the silylated (BSTFA) products confirmed the absence

of the secondary alcohol.

5.3 *Discussion*

The carboranyl group in C(1)-homoallyl and C(1)-homoallyl-C(2)-methyl derivatives exhibits a diminished but still appreciable directive effect in hydroboration. The average distribution indicated by ^{1}H NMR and GC analyses was 92% terminal addition and 8% internal. Comparison with several 3-butenyl derivatives revealed (Chart 11, pg. 17) that the polar influence of a β-carboranyl group is considerable and resembles that of a methoxy substituent.

In these systems, oxidation with sodium perborate yielded up to 10% butyl-*o*-carborane. In all the other systems, alkyl carboranes were not formed when sodium perborate was used as the oxidant.

When the carboranyl group is more remote from the double bond, the directive effect diminishes. Thus, in 1-(4-pentenyl)-*o*-carborane and 1-(7-octenyl)-*o*-carborane, the hydroboration (Chart 1, pg. 3) affords the anticipated 96:4 primary to secondary boron distribution.

Formation of the internal boron derivatives was avoided with the employment of 9-BBN and Chx_2BH as hydroborating agents. Better than 98% selectivity for the terminal carbon was obtained in all these cases.

Experimental Section

The reaction flask and other glassware were stored overnight in an oven at 150°C and assembled in a stream of dry nitrogen gas. Syringes were assembled and fitted with needles while hot and cooled in a stream of dry nitrogen gas. The handling of air sensitive materials was carried out in a dry box or in a glove bag under argon or nitrogen.

Proton (^{1}H NMR) and carbon (^{13}C NMR) spectra were obtained on a Bruker AMX 400 spectrometer at 400.13 and 100.62 MHz, respectively. Boron (^{11}B NMR) spectra were obtained at 128.38 MHz on the Bruker AMX 400 spectrometer. Chemical shifts for ^{1}H NMR and ^{13}C NMR spectra were referenced to $SiMe_4$ (0.00 ppm) and measured with respect to residual protons in the deuterated solvent. Chemical shift values for ^{11}B spectra were referenced relative to $BF_3{\cdot}OEt_2$ (0.00 ppm). Coupling constants (J) are given in Hertz. Resonances observed upfield of the references were assigned negative chemical shift values in all cases. Mass spectra were recorded on GC/MS (Hewlett-Packard 5890 gas chromatograph and 5970 series mass selective detector equipped with a crossbonded 100% dimethylpolysiloxane column.) Melting points were determined on a Thomas-Hoover capillary melting point apparatus. The melting points were uncorrected.

The gas chromatographic analyses were performed on either a Varian 3700 Model or a Hewlett-Packard 5750 model chromatograph. The following columns were used: 5% SE-30 on Chromosorb W, 10 ft x 0.25 in. and 10% SE-30 on Chromosorb W, 10 ft x 0.25 in.; and 10% Carbowax 20M on Chromosorb W, 10 ft

x 0.25 in. Products were isolated by HPLC on a Varian Model 5000 HPLC which had a programmable gradient elution capability on an ODC-3 column.

The *o*-carborane, vinyl-*o*-carborane, methyl-*o*-carborane, and hexyl-*o*-carborane were purchased from Dexsil Corp.

Hydroboration of Vinyl-*o*-carborane with BMS (3:1). In a 25 mL flask equipped with a septum inlet, magnetic stirring bar, and connecting tube attached to a mercury bubbler was placed, under Ar, vinyl-*o*-carborane (3.11 mmol, 0.530 g) in THF (2.5 mL). The reaction flask was cooled to 0 °C. To it was added BMS (1.05 mmol, 0.590 mL of a 1.78 M solution in THF) dropwise via syringe. The reaction was allowed to stir at 25 °C for 20 h. The solution was analyzed for residual hydride by addition of H_2O (1 mL). This resulted in the evolution of hydrogen (0.87 mmol) indicating a maximum of 72% consumption of vinyl-*o*-carborane in the reaction. The reaction mixture was oxidized, at 0 °C, by addition of THF (10 mL), H_2O (10 mL) and of sodium perborate (4.66 mmol, 0.717 g). This mixture was stirred vigorously overnight at 25 °C. The aqueous phase was saturated with NaCl and the two phases were separated. The aqueous layer was extracted with ether (5 x 10 mL). The combined organic phase was dried over anhydrous $MgSO_4$ and the product was analyzed by GLC using a 6 ft column packed with 5% SE-30, on chromosorb W using tetradecane (0.295 mmol, 50.2 mg) as an internal standard. This analysis gave the following results: vinyl-*o*-carborane (25%), 1-(*n*-ethyl)-*o*-carborane (4%), 1-*o*-carboranyl-1-ethanol (35%), 2-*o*-carboranyl-1-ethanol (34%), and an ethyl-*o*-carboranyl·THF adduct (2%). Total yield of carborane products was 95%.

In a separate experiment, using the experimental setup described above, to vinyl-*o*-carborane (1.00 mmol, 0.170 g) in THF (0.7 mL), was added at 0 °C, BMS (0.35 mmol, 0.20 mL of a 1.75 M solution in THF) dropwise via a syringe. The reaction was allowed to stir at 25 °C for 4 h. Treatment with a solution of sodium hydroxide (2.00 mmoL, 0.66 mL of a 3 N solution) and hydrogen peroxide (6.6 mmoL, 0.66 mL of a 30% solution) at 0 °C resulted in an exothermic reaction. The mixture was allowed to stir for 3 h at 25 °C and then heated for 1 h at 50 °C. The aqueous phase was saturated with NaCl. The aqueous layer was extracted with ether (5 x 15 mL) and the combined ether extracts were dried over anhydrous $MgSO_4$. Following solvent evaporation the residue was examined by ^1H NMR using tetradecane (0.154 mmol, 30.5 mg) as internal standard; it gave the following results: vinyl-*o*-carborane (31%), 1-(*n*-ethyl)-*o*-carborane (22%), 1-*o*-carboranyl-1-ethanol (16%), and 2-*o*-carboranyl-1-ethanol (31%). The total yield of carborane products was 93%. A few drops of the crude product were placed in a vial and 0.1 mL of *N,O*-bis(trimethylsilyl)acetamide in pyridine was added. The mixture was shaken and warmed to 30 °C for 5 min. Examination of this mixture by ^{11}B NMR indicated the presence of cage degradation products. Thus, the pyridine procedure was discarded and a more efficient silylating agent, *N,O*-bis (trimethylsilyl)trifluoroacetamide, with 1% trimethylchlorosilane, was used. An aliquot of the crude product was treated with this silylating mixture at 30 °C for 1 h without any cage decomposition being observed. The isomeric silyl ethers were analyzed by GC on a 6ft 5% SE-30, on Chromosorb W column. The results indicated an isomer distribution, primary to

secondary alcohols of 87:13

The crude products were separated by preparative GC on a 7% SE-30 column on Chromosorb W. 2-*o*-Carboranyl-1-ethanol: mp 51 °C; ^{1}H NMR (CD_3CN) δ 4.35 (1H, s), 3.61 (2H, t, J= 6.4 Hz), 2.45 (2H, t, J= 6.4 Hz); ^{13}C NMR ($CDCl_3$) δ 73.1, 60.6, 60.4, 39.7; ^{11}B NMR ($CDCl_3$) δ -1.72 (1B, d), -4.78 (1B, d), -8.67 (2B, d), -12.9 (2B, d); High resolution MS (FAB) m/z calcd for $C_4H\ B_{10}O$ 190.2132 found 190.2102. 1-*o*-carboranyl-1-ethanol: oil; ^{1}H NMR (CD_3CN) δ 4.34 (1H, s), 4.26 (1H, 9, J= 6.4 Hz), 1.30 (3H, d, J= 6.4 Hz); ^{13}C NMR ($CDCl_3$) δ 79.5, 68.9, 58.6, 23.6 ; ^{11}B NMR (32.1 MHz) ($CDCl_3$) δ -3.61 (2B, d), -2.02 (8B, d); High resolution MS (FAB) m/z calcd for $C_4H_{14}B_{10}O$ 190.2132 found 190.2134.

1-(*n*-Ethyl)-*o*-carborane: mp 38-40 °C (163); ^{1}H NMR acetone-d_6 δ 4.52 (1H, s), 2.37 (2H, 9, J =7.5 Hz), 1.09 (3H, t, J =7.5 Hz); ^{1}H NMR ($CDCl_3$) δ 3.56 (1H, s), 2.29 (2H, 9, J =7.6 Hz), 1.09 (3H, t, J =7.6Hz); ^{13}C NMR ($CDCl_3$) δ 76.4, 60.9, 31.6, 13.5; ^{11}B NMR ($CDCl_3$) δ -2.65 (1B, d), -6.21 (1B, d), -9.58 (2B, d), -11.7 (2B, d), -12.6 (2B, d), -13.4 (2B, d).

Synthesis of 1-(*n*-Ethyl)-*o*-carborane. Vinyl-*o*-carborane (17.6 mmoL, 3.00 g) in 30 ml of hexane was hydrogenated over 0.3 g of Raney nickel at 100 °C and 85 atm pressure for 5 h. The solvent was distilled off from the filtrate and the residue was recrystallized from heptane. This afforded a 95% yield of 1-(*n*-ethyl)-*o*-carborane (mp 38-39 °C).

Hydroboration of Vinyl-*o*-carborane with BMS (1:1). This reaction was run using the experimental setup described above. To a solution of vinyl-*o*-carborane (2.12 mmol,

0.360 g) in THF (2 mL) at 0 °C was added BMS (2.11 mmol, 1.08 mL of a 1.95 *M* solution in THF) dropwise with stirring. The mixture was allowed to stir for 24 h at 25 °C. The solution was cooled to 0 °C and oxidized by the sequential addition of THF (5 mL), an equal volume of H_20 and sodium perborate (3.13 mmol, 0.482 g). The mixture was stirred at room temperature for 13 h, and at 40 °C for 1 h. The two phases were separated and the aqueous layer was extracted with additional Et_2O (2 x 10 mL). The combined organic phases were then dried with anhydrous $MgSO_4$ and tetradecane was added (0.123 mmol, 24.4 mg) as an internal standard. Analysis by GC using 5% SE-30 on Chromosorb W column gave: vinyl-*o*-carborane (1.3%), 1-(*n*-ethyl)-*o*-carborane(8.4%),1-*o*-carboranyl-1-ethanol(45.2%),2-*o*-carboranyl-1-ethanol (43.6%), an ethyl-*o*-carborane·THF adduct (1.2%), and a trace of *o*-carborane (0.3%). Careful evaporation of the solvent gave 0.370 g of products (tetradecane subtracted) which by analysis by ^1H NMR, contained 9.9% 1-(*n*-ethyl)-*o*-carborane, 45.6% 1-*o*-carboranyl-1-ethanol, 39.5% 2-*o*-carboranyl-1-ethanol, and ~5% ethyl-*o*-carborane·THF adduct (5%).

Monitoring the Rate of Reaction of Vinyl-*o*-carborane with BMS. Reaction of 7Intermediate with Hexene. Into a 5 mm NMR tube, in a dry box, were placed sequentially vinyl-*o*-carborane (1.27 mmol, 0.216 g), dibromobenzene (0.106 mmol, 25.0 mg), and THF-d_8 (0.5 mL). The NMR tube was then capped with a plastic stopper and on the top of it an additional rubber septum was secured. The NMR tube was placed in an ice bath, and under argon, BMS (0.43 mmol, 0.22 mL of a 1.92 *M* solution in THF) was carefully added via a syringe. The NMR tube was

withdrawn from ice, dried, shaken, and monitored by ^{1}H NMR. When the quantity of olefin consumed was determined to be 65% (~28 h), the appropriate amount of hexene plus 26% excess (0.52 mmoles, 42.6 mg) was added at 25 °C. The reaction was stirred at 25 °C and monitored by ^{11}B NMR and ^{1}H NMR. At the end of 2 h the contents of the NMR tube were carefully washed in a dry box with THF (20 mL) into a separate flask which contained sodium perborate (1.930 mmoL, 297.0 mg). The flask was then sealed with a rubber septum and removed from the dry box. Water (10 mL) was added via a syringe and the solution was stirred at 25 °C for 8 h. The layers were separated and the aqueous layer was extracted with additional Et_2O (2 x 10 mL). The combined organic phase was dried over anhydrous $MgSO_4$ and most of the solvent was evaporated. Tetradecane (0.215 mmol, 42.6 mg) was added and the yield of alcohols was determined by GC using a 10% Carbowax 20M column on Chromosorb W. The yield of hexanol was found to be 70%. The ratio of 1-hexanol to 2-hexanol was 97:3.

Monitoring of the Rate of Vinyl-*o*-carborane with BMS. Reaction with Styrene. In a 25 mL flask equipped with a side-arm, fitted with a rubber septum cap was placed, under Ar, vinyl-*o*-carborane (3.28 mmol, 0.557 g) in THF (2.5 mL), followed by hexadecane (0.737 mmoL, 0.210 mL) used as an internal standard for GC. The solution was added at 0 °C to BMS (1.08 mmoL, 0.570 mL of a 1.89 *M* solution in THF) dropwise via syringe. Aliquots were withdrawn at 30 min intervals and the unreacted hydride was destroyed in a H_2O/THF mixture. Then, ether (0.5 mL) was added and the organic phase was examined by GC for unreacted vinyl-*o*-carborane.

After 28 h the reaction products were added to freshly distilled styrene (0.960 mmoL, 0.11 mL) and the reaction mixture was allowed to stir at 25 °C for 16 h. Oxidation with sodium perborate (4.86 mmoL, 747 mg) and work-up in the usual manner afforded, by GC analysis on a 10% carbowax 20M column, 85% of α- and ß-phenylethyl alcohols in a ratio of 4.8:95.2.

Reaction of Vinyl-*o*-carborane with Dicyclohexylborane. In a 25 mL two-necked flask, containing cyclohexene (2.8 mmol, 0.29 mL) in THF (1 mL), immersed in an ice-bath, BMS (1.38 mmol, 0.71 mL of a 1.94 *M* solution in THF) was added via syringe. The reaction was allowed to stir at 0 °C for 3 h. Vinyl-*o*-carborane was added (1.38 mmol, 0.235 g) in THF (1 mL) under a blanket of Ar and the reaction mixture was allowed to stir at 25 °C for 30 h. Oxidation was performed by the sequential addition of THF (5 mL), H_2O (5 mL), and sodium perborate (6.21 mmol, 0.955 g). The reaction was allowed to stir for 12 h with vigorous stirring. The organic layer was separated and the aqueous layer extracted with ether (4 × 10 mL). The combined ether extracts were washed with saturated NaCl solution and dried over anhydrous $MgSO_4$. The solvent was evaporated to afford 0.510 g of a clear liquid, which upon analysis by ^1H NMR using hexadecane (0.620 mmol, 140 mg) as an internal standard gave 2-*o*-carboranyl-1-ethanol (87%), 1-*o*-carboranyl-1-ethanol (3%), 1-(*n*-ethyl)-*o*-carborane (2%), and cyclohexyl and furanyl adducts with ethyl-*o*-carborane (8%). The total yield of carborane products was 96%. An aliquot of the dried extract was treated with *N,O*-bis(trimethylsilyl)trifluoroacetamide containing 1% trimethylchlorosilane. This was heated for 1 h at 35 °C. The resulting TMS

derivatives of the isomeric alcohols were analyzed by GC/MS. A distribution of primary to secondary alcohols of 98:2 was found.

Reaction of Vinyl-*o*-carborane with 9-BBN in Hexanes. Vinyl-*o*-carborane (1.023 mmol, 174.0 mg) in a 10 mm NMR tube was added, in the dry box, 9-BBN (1.07 mmol, 2.14 mL of a 0.5 *M* solution in hexane) at 25 °C. The NMR tube was placed in a sonicator and the sonic disruptor was switched on. The reaction was monitored at 30 min intervals by ^{1}H NMR for loss of olefin. At the end of 24 h, the reaction mixture was oxidized by the sequential addition of H_2O (5 mL), THF (5 mL), and sodium perborate (4.815 mmol, 741.0 mg). After 14 h at room temperature, the contents of the tube were washed with ether (10 mL) into a separatory funnel, the tube washed with an equal volume of water, and the organic phase separated.

The solvent was evaporated to give 0.350 g of a viscous liquid. To it was added dibromobenzene (0.159 mmol, 37.6 mg) and the crude product was examined by ^{1}H NMR. This analysis indicated the presence of 2-*o*-carboranyl-1-ethanol (96%), 1-*o*-carboranyl-1-ethanol (1%), and 1-(*n*-ethyl)-*o*-carborane (3%). The total yield of the reaction was 94%. An aliquot of the crude product was treated with 0.4 mL of *N*,*O*-bis(trimethylsilyl)trifluoroacetamide containing 1% trimethylsilylchloride and the mixture was heated for 1 h at 30 °C. Examination of the product mixture by GC/MS indicated that the isomeric silyl ethers separated nicely. Integration indicated an isomer distribution for primary to secondary alcohols of 98.8:1.20.

The Reaction of 1-Isopropenyl-*o*-carborane with BMS and BH_3·THF. In a 25 mL flask equipped as described previously was placed 1-isopropenyl-*o*-carborane (1.525

mmol, 283.0 mg). The solid was dissolved by addition of THF (1 mL) and the reaction flask was cooled to 0 °C. To it was added BMS (0.52 mmol, 0.29 mL of a 1.8 *M* solution in THF) dropwise via syringe. The reaction mixture was kept at room temperature with stirring. At the end of 8 h the residual hydride was destroyed by addition of H_2O (1 mL). The liberated hydrogen gas indicated the presence of 0.27 mmoles of unreacted borane reagent (48% conversion). The reaction mixture was oxidized in the usual way by the addition of sodium perborate (1.625 mmol, 250.0 mg). The reaction mixture was stirred at 25 °C for 8 h and worked up in the usual way. ^{1}H NMR analysis of the product mixture using hexadecane (0.356 mmol, 80.5 mg) as an internal standard indicated the presence of carborane products in 94% yield. The distribution of produts was as follows: 1-isopropenyl-*o*-carborane (57%) and 2-*o*-carboranyl-1-propanol (43%).

In a separate experiment isopropenyl-*o*-carborane (1.120 mmol, 221.0 mg) in THF (1 mL) was treated with BH_3·THF (0.41 mmol, 0.41 mL of 1.0 *M* solution) at room temperature for 48 h. At the end of this period, the reaction mixture was oxidized by the simultaneous addition of sodium hydroxide (0.60 mmol, 0.20 mL of a 3.0 *N* solution) and hydrogen peroxide (2.0 mmol, 0.20 mL of a 30% solution), at 25 °C for 6 h. The reaction mixture was then extracted with ether (4 x 30 mL), and the combined ether extracts were dried over anhydrous $MgSO_4$. The ether was evaporated and the crude products was added dibromobenzene (0.186 mmol, 47.2 mg) as an internal standard for ^{1}H NMR determination. The total yield of carborane products was 90%. The distribution of products was 2-*o*-carboranyl-1-propanol

(70%), 2-*o*-carboranylpropane (5%), *o*-carborane (3%), and isopropenyl-*o*-carborane (22%). An aliquot of the crude product was treated with *N,O*-bis(trimethylsilyl)trifluoroacetamide containing 1% trimethylchlorosilane to afford only the silyl ether of the 2-*o*-carboranyl-1-propanol. No TMS derivative of the 2-*o*-carboranyl-2-propanol was detected. The 2-*o*-carboranyl-1-propanol was partially purified by recrystallization from hexanes: ^{1}H NMR (acetone-d_6) δ 4.77 (1H, s), 3.60 (1H, dd, J = 6.4 Hz), 3.53 (1H, dd, J = 6.4 Hz), 2.55 (1H, m), 1.15(3H, d, J = 7.2 Hz); ^{13}C(^{1}H) COSY NMR (acetone-d_6) δ 79.5, 65.1 (3.60, 3.53), 61.1 (4.77), 41.3 (2.55), 17.3 (1.15); ^{11}B NMR (acetone-d_6) δ -2.12 (1B, d), -3.79 (1B, d), -8.61 (2B, d), -10.32 (4B, d), -12.04 (2B, d).

The Reaction of 1-Propenyl-*o*-carborane with BH_3·THF. To a solution of 1-propenyl-o-carborane (0.494 mmol, 90.9 mg) in THF (0.5 mL) contained in a 5 mm tube was added at 0 °C, BH_3·THF (0.17 mmol, 0.17 mL of a 1.0 *M* solution) and the reaction was monitored by ^{1}H NMR and ^{11}B NMR for 31 h. Oxidation at 0 °C with sodium peroxide (0.30 mmol, 0.10 mL of a 3.0 *N* solution) and hydrogen peroxide (1.0 mmol, 0.10 mL of a 30% solution) afforded, after separation of the organic phase and drying over anhydrous $MgSO_4$, 270.0 mg of a viscous clear liquid. Addition of acetone dissolved 85 mg of the products and the remaining was insoluble. Using dibromobenzene (0.0744 mmol, 18.9 mg) as internal standard indicated, by ^{1}H NMR, a 96% total yield of carborane products. This analysis gave the following: 1-propenyl-*o*-carborane (34%), 1-*o*-carboranyl-1-propanol (47%), 3-*o*-carboranyl-2-propanol (5%), 1-(*n*-propyl)-*o*-carborane (12%), *o*-carborane (2%). 1-*o*-Carboranyl-

1-propanol : ^{1}H NMR (acetone-d_6) δ 4.70 (1H, s), 4.03 (1H, m), 1.28 (2H, m), 0.89 (3H, t, J = 7.2 Hz); ^{13}C (^{1}H) COSY NMR (acetone-d_6) δ 79.9, 73.7 (4.03), 58.6 (4.70), 30.2 (1.28), 10.9 (0.87).

Hydroboration of 1-Allyl-*o*-carborane with BH_3·THF. To a 10 mm NMR tube in a dry box was added 1-allyl-*o*-carborane (1.192 mmol, 224.1 mg) in THF (1 mL). To it was added BH_3·THF (0.41 mmol, 0.41 mL of a 1.0 *M* solution), and the reaction was stirred with a vortex stirrer at room temperature and periodically monitored by ^{1}H NMR for unreacted olefin. At the end of 5 h the reaction mixture was cooled to 0 °C and the organoboranes was oxidized by the addition of sodium peroxide (0.63 mmol, 0.21 mL of a 3.0 *N* solution) and hydrogen peroxide (2.1 mmol, 0.21 mL of a 30% solution). The reaction mixture was maintained at room temperature for 12 h with vigorous stirring. The two phases were separated and the aqueous phase was extracted with ether (5 x 10 mL). The combined organic phase was washed with saturated NaCl solution and dried over anhydrous $MgSO_4$. Evaporation of the solvent afforded 240.0 mg of products. To the crude product was added dibromobenzene (0.0790 mmol, 20.0 mg) as a standard for ^{1}H NMR analysis. The total yield of carborane products was 98%. The following results were obtained: 3-*o*-carboranyl-1-propanol (54%), 3-*o*-carboranyl-2-propanol (31%), and 1-(*n*-propyl)-*o*-carborane (6%), and radical products (9). An aliquot of the dried extract, ~20 mg, was treated with 0.3 mL of *N*,*O*-bis(trimethylsilyl)trifluoroacetamide containing 1% trimethylchlorosilane. The mixture was heated at 30 °C for 1 h. The resulting TMS-ethers were analyzed by GC/MS to afford a primary to secondary alcohol ratio of

66:34.

Hydroboration of 1-Allyl-*o*-carborane with BH_3·THF. To a 25 mL flask in a dry box was added 1-allyl-*o*-carborane (1.531 mmol, 282.0 mg) in THF (2 mL). To it was added BH_3·THF (0.56 mmol, 0.56 mL of a 1.0 *M* solution), and the reaction was stirred at room temperature fot 5 h. At the end of 5 h the reaction mixture was cooled to 0 °C and the organoboranes oxidized by addition of H_2O (5 mL), an equal volume of THF and sodium perborate (2.52 mmol, 387 mg). The reaction mixture was maintained at room temperature for 12 h with vigorous stirring. The two phases were separated and the aqueous phase was extracted with ether (5 x 10 mL). The combined organic phase was washed with saturated NaCl solution and dried over anhydrous $MgSO_4$. Evaporation of the solvent afforded 305.0 mg of products. To the crude product was added dibromobenzene (0.0660 mmol, 16.8 mg) as a standard for ^1H NMR analysis. The total yield of carborane products was 96%. The following results were obtained: 3-*o*-carboranyl-1-propanol (60%), 3-*o*-carboranyl-2-propanol (31%), and 1-(*n*-propyl)-*o*-carborane (9%). An aliquot of the dried extract, ~20 mg, was treated with 0.3 mL of *N,O*-bis(trimethylsilyl)trifluoroacetamide containing 1% trimethylchlorosilane. The mixture was heated at 30 °C for 1 h. The resulting TMS-ethers were analyzed by GC/MS to afford a primary to secondary alcohol ratio of 65:35.

The products of this reaction were separated by HPLC using mixtures of 5-10% H_2O in MeOH as eluant. 3-*o*-Carboranyl-1-propanol: (oil); spectroscopic data were in agreement with literature (151).

Hydroboration of 1-allyl-*o*-carborane with Dicyclohexylborane. To a 25 mL two-necked flask under Ar, were placed at 0 °C BMS (2.26 mmol, 1.20 mL of a 1.88 *M* solution in THF) and cyclohexene (4.74 mmol, 0.48 mL). To the reaction mixture was added THF (3 mL) and allowed to stir at 0 °C for 3 h. To the dicyclohexylborane (2.26 mmol) was added, at 0 °C, 1-allyl-*o*-carborane (1.05 mmol, 193.0 mg) in THF (2 mL). The reaction was allowed to proceed for 6 h at 25 °C with stirring. The organoborane was diluted with THF (5 mL), H_2O (5 mL) and sodium perborate (10.0 mmol, 1.540 g) was added. The oxidation proceeded for 12 h at 25 °C. The two phases were separated and the aqueous phase was extracted with diethyl ether (5 x 30 mL). The combined organic phase was predried with NaCl and dried over anhydrous $MgSO_4$ to afford after concentration 630.0 mg of a clear liquid. Tetradecane (0.090 mmol, 18.0 mg) was added as an internal standard, and analysis by ^1H NMR afforded: 3-*o*-carboranyl-1-propanol (95%), 3-*o*-carboranyl-2-propanol (1%), and traces of radical products. An aliquot of the crude product was treated with 0.3 mL of *N,O*-bis(trimethylsilyl) trifluoroacetamide containing 1% trimethylchlorosilane. The resulting TMS derivative of the alcohols were analyzed by GC/MS and indicated a ratio of primary to secondary alcohols of 99:1: ^1H NMR ($CDCl_3$) δ 3.64 (2H, t,J=6.0 Hz), 3.59 (1H, s), 2.35 (2H, m), 1.72 (2H, m); ^{13}C NMR ($CDCl_3$) δ 75.14, 61.24, 61.50, 34.86, 32.03; ^{11}B NMR(acetone-d_6) δ -1.78 (1B, d), -5.02 (1B, d), -8.51 (2B, d), -10.34 (4B, d), -11.83 (2B, d). 3-*o*-Carboranyl-2-propanol: oil; ^1H NMR ($CDCl_3$) δ 4.03 (1H, m), 3.63 (1H, s), 2.35 (2H, m), 1.20 (3H, d, J = 6.1 Hz); ^{13}C NMR ($CDCl_3$) δ 73.00, 66.56, 59.82, 45.57, 24.23. 1-(*n*-Propyl)-*o*-carborane: mp 69

°C ; ^{1}H NMR (CD_3CN) δ 4.03 (1H, s), 2.20 (2H, m), 1.46 (2H, m), 0.87 (3H, t, J = 7.1 Hz); ^{13}C NMR (CD_3CN) δ 76.5, 62.3, 39.7, 22.9, 13.2.

Hydroboration of 1-Allyl-*o*-carborane with 9-BBN. Into a 10 mm NMR tube in a dry box was placed a solution of 1-allyl-*o*-carborane (1.37 mmol, 253.0 mg) in THF (1.5 mL). To it was added 9-BBN (1.44 mmol, 2.87 mL of a 0.5 *M* solution in hexane) at 25 °C. The NMR tube was placed in a sonicator and the sonic disruptor was switched on and the progress of the reaction was monitored by ^{11}B NMR. At the end of 5 h the organoborane was added to water (5 mL) and THF (5 mL), and the mixture was oxidized by the addition of sodium perborate (6.480 mmol, 997.0 mg). The reaction mixture was stirred vigorously for 12 h at 35 °C. The two phases were separated and the aqueous phase was extracted with diethyl ether (3 x 30 mL). The combined organic phases were washed with saturated NaCl and dried over anhydrous $MgSO_4$. Evaporation of the solvent at reduced pressure afforded 471.0 mg of a viscous clear liquid. To the product was added dibromobenzene (0.160 mmol, 40.6 mg) as an internal standard. Examination of the resulting mixture by ^{1}H NMR indicated a 97% yield of products. The individual products were: 3-*o*-carboranyl-1-propanol (79%), 3-*o*-carboranyl-1-propene (15%), 1-(*n*-propyl)-*o*-carborane (4%), and 2% radical products. An aliquot of the crude products was treated with 0.4 mL of *N,O*-bis(trimethylsilyl)trifluoroacetamide containing 1% trimethylsilyl chloride, heated for 1 h at 30 °C and analyzed by GC/MS. The ratio of primary to secondary TMS derivatives of the corresponding alcohols was found to be 99:1.

Hydroboration of 1-Allyl-2-hexyl-*o*-carborane with BH_3·THF. To a solution of

1-allyl-2-hexyl-*o*-carborane (0.760 mmol, 203.0 mg) in THF (1 mL) was added BH_3·THF (0.27 mmol, 0.27 mL of a 1.0 *M* solution) at 30 °C in a dry box. At the end of 6 h sodium perborate (1.21 mmol, 186.0 mg), was added to the reaction mixture in the dry box. Then, the reaction flask was removed from the box and H_2O (5 mL) with THF (5 mL) were added. The mixture was maintained at room temperature for 12 h with vigorous stirring. The two phases were separated and the aqueous phase was extracted with ether (5 x 30 mL). The combined organic phase was washed with saturated NaCl solution and dried over crushed molecular sieves to afford, after solvent evaporation, 96% of carborane products. ^{1}H NMR analysis of the product mixture using dibromobenzene (0.0850 mmol, 20.0 mg) as an internal standard afforded: 3-hexyl-*o*-carboranyl-1-propanol (61%), 3-hexyl-*o*-carboranyl-2-propanol (30%), 3-hexyl-*o*-carboranyl·THF adducts (5%), and 1-hexyl-2-propyl-*o*-carborane (4%). An aliquot of the crude product was treated with 4 mL of *N,O*-bis(trimethylsilyl)trifluoroacetamide, heated for 3 h at 30 °C and analyzed by GC/MS to give a 68:32 ratio of primary to secondary alcohols. The two isomeric alcohols were separated by gas chromatography using a 7% SE-30 on Chromosorb W. *3-Hexylcarboranyl-1-propanol*: mp 54 °C; ^{1}H NMR (CD_3CN) δ 3.485 (2H, t, J = 6.0 Hz), 2.320 (2H, m), 2.238 (2H, m), 1.701 (2H, m), 1.525 (2H, m), 1.291 (6H, m), 0.883 (3H, t, J = 7.2 Hz); ^{13}C NMR ($CDCl_3$) δ 80.3, 79.5, 61.6, 35.2, 32.6, 31.8, 31.4, 29.8, 29.0, 22.52, 14.0; ^{11}B NMR(CD_3CN) δ -3.81 (2B, d), -9.38 (8B, d). High resolution MS (FAB): m/z calcd for $C_{11}H_{30}B_{10}O$ 288.2862 found 288.2864. *3-Hexylcarboranyl-2-propanol*: mp oil; ^{1}H NMR (CD_3CN) δ 3.914 (1H, m, J = 5.28 Hz),

2.886 (1H, d, J = 5.2 Hz, OH), 2.294 (2H, m), 2.253 (2H, m), 1.515 (2H, m), 1.287 (6H, m), 1.15 (3H, d, J = 6.2 Hz), 0.865 (3H, t, J = 7.02 Hz). High resolution MS (FAB) m/z calcd for $C_{11}H_{30}B_{10}O$ 288.3227 found 288.3195.

Hydroboration of 1-Allyl-2-hexyl-o-carborane with 9-BBN. To a 25 mL flask fitted with the usual setup for hydroboration, 1-allyl-2-hexyl-*o*-carborane (0.850 mmol, 228.0 mg) was added 9-BBN (0.940 mmol, 1.88 mL of a 0.50 *M* solution in hexane) at 25 °C. The flask was sonicated at 30 °C for 12 h. The organoborane was diluted with a THF-water mixture, 5mL each, and sodium perborate (5.17 mmol, 795.0 mg) was added. The reaction was stirred vigorously for 3 h at 25 °C and then 1 h at 50 °C. The two phases were separated and the aqueous phase was extracted with diethyl ether (5 x 10 mL). The combined organic phase was dried over anhydrous $MgSO_4$ and concentrated *in vacuo*. To the product was added dibromobenzene (0.383 mmol, 58.9 mg) as an internal standard. Analysis of the product mixture by ^{1}H NMR gave the following: 3-hexylcarboranyl-1-propanol (88%) and 3-hexylcarboranyl-2-propanol (2%).

Hydroboration of 1-Allyl-2-hexyl-*o*-carborane with Dicyclohexylborane (Chx_2BH).- To a 25 mL two-necked flask under N_2, were placed at 0 °C BMS (0.860 mmol, 0.340 ml of a 2.53 *M* solution in THF) and cyclohexene (1.78 mmol, 0.18 mL). The reaction was diluted with THF (3 mL), and allowed to stir at 0 °C for 4 h. To the dicyclohexylborane (0.860 mmol) was added, at 0 °C, 1-allyl-2-hexyl-*o*-carborane (0.852 mmol, 227.0 mg) in THF (2 mL). The flask was stirred for 6 h at 25 °C. The organoborane was diluted with THF (5 mL) and an equal volume of water. Sodium

perborate (5.160 mmol, 794.0 mg) was added and the reaction mixture was stirred at 30 °C for 6 h. The two phases were separated and the aqueous phase was extracted with ether (5 x 30 mL). The solvent was evaporated and dibromobenzene (0.411 mmol, 104.5 mg) was added as an internal standard. Examination of the product mixture by ^{1}H NMR gave the following results: 3-hexylcarboranyl-1-propanol (92%), 3-hexylcarboranyl-2-propanol (2%), and radical products (6%). The total yield of carborane products was 96%.

Hydroboration of 1-Crotyl-*o*-carboane with BH_3·THF. To a solution of 1-crotyl-*o*-carborane (1.139 mmol, 228.8 mg) in tetrahydrofuran (1 mL) was added BH_3·THF (0.38 mmol, 0.38 mL of a 1.0 *M* solution) at 30 °C in a dry box. After 30 h the reaction mixture was taken from the dry box. After cooling to 0 °C, sodium hydroxide solution (0.6 mmol, 0.2 mL of a 3.0 *M* solution) and hydrogen peroxide (2.0 mmol, 0.2 mL of a 30% solution) were added. The mixture was maintained at room temperature for 12 h with stirring. The two phases were separated and the aqueous phase was extracted with ether (3 x 10 mL). The combined organic phase was washed with saturated NaCl solution and dried over crushed molecular sieves. Evaporation of the solvent gave 245.0 mg of a clear liquid. Dibromobenzene (0.121 mmol, 28.6 mg) was added as an internal standard, and the product mixture was examined by ^{1}H NMR; it afforded the following product distribution: 1-*o*-carboranyl-2-butanol (89%), 4-*o*-carboranyl-2-butanol (9%). The total yield of carborane products was 94%. An aliquot of the crude product was treated with 0.3 mL of *N,O*-bis(trimethylsilyl)trifluoroacetamide containing 1% trimethylchlorosilane and heated

for 1 h at 30 °C. The resulting TMS derivatives of the alcohols were analyzed by GC/MS. This gave ß to γ alcohols ratio of 91:9.

Hydroboration of 1-Crotyl-*o*-carborane with 9-BBN in Hexanes. To a 10 mm NMR tube, in a dry box, was placed 1-crotyl-*o*-carborane (1.17 mmol, 234.0 mg) and hexanes (1 mL). Then 9-BBN (1.29 mmol, 2.57 mL of a 0.5 *M* solution in hexanes) was added at 30 °C. The reaction was placed in the sonic disruptor and examined by ^{11}B NMR at 30 min intervals (external reference). After 20 h the signal due to 9-BBN, at 28 ppm, completely disappeared. Then the reaction was cooled to 0 °C and oxidized by the simultaneous addition of sodium hydroxide (2.58 mmol, 0.86 mL of a 3.0 *N* solution) and hydrogen peroxide (9 mmol, 0.9 mL of a 30 % solution). The flask was warmed to room temperature and allowed to stir for 4 h. The crude product was transferred to a separatory funnel and washed with water and diethyl ether (6 × 15 mL). The organic extracts were dried over $MgSO_4$ and the solvent was evaporated to afford a clear liquid. After dibromobenzene (0.0930 mmol, 21.9 mg) was added as an internal standard, analysis of the resulting mixture by ^1H NMR gave the following: 1-(*n*-butyl)-*o*-carborane (11%), 1-*o*-carboranyl-2-butanol (83%), and 4-*o*-carboranyl-2-butanol (6%). The total yield of the recovered carborane products was 97%. An aliquot of the crude products was treated with 0.3 mL of *N,O*-bis(trimethylsilyl)trifluoroacetamide, heated for 1 h at 30 °C, and analyzed by GC/MS to give ß to γ ratio of alcohols of 89:11. The oxidation products were further examined by H/H COSY and C/H COSY experiments. <u>1-*o*-Carboranyl-2-butanol</u>: ^1H NMR (acetone-d_6) δ 4.68 (1H, s), 3.64 (1H, m), 2.38 (2H, m), 1.41 (2H,

m), 0.84 (3H, t, 7.6 Hz); ^{13}C NMR (acetone) δ 76.5, 71.9, 63.4, 44.5, 31.3, 9.9; ^{11}B NMR (acetone-d_6) δ -1.05 (1B, d), -4.06 (1B, d), -8.27 (6B, d), -11.14 (2B, d); 4-*o*-carboranyl-2-butanol: ^1H NMR (acetone-d_6) δ 4.62 (1H, s), 3.64(1H, m), 2.36(2H, m), 1.38(2H, m), 1.09(3H, d, J = 6.4 Hz).

Hydroboration of 1-Homoallyl-*o*-carborane with BH_3·THF. To a solution of 1-homoallyl-*o*-carborane (1.84 mmol, 368.0 mg) in tetrahydrofuran (1 mL) was added BH_3.THF (0.63 mmol, 0.63 mL of a 1.0 *M* solution) at 25 °C. After 3 h the reaction mixture was cooled to 0 °C and oxidized by addition of H_2O (5 mL), THF (5 mL) and sodium perborate (2.75 mmol, 423.0 mg). The reaction mixture was maintained at room temperature for 12 h with vigorous stirring. The two phases were separated and the aqueous phase was extracted with ether (6 x 10 mL). The combined organic phase was washed with saturated NaCl solution and dried over anhydrous $MgSO_4$ to afford after evaporation of the solvent 379.0 mg of an oily material. GC/MS analysis of the product mixture using tetradecane (0.120 mmol, 39.5 mg) as an internal standard revealed by ^1H NMR analysis the following product distribution: 4-*o*-carboranyl-1-butanol (70%), 4-*o*-carboranyl-2-butanol (5%), 4-(*n*-butyl)-*o*-carborane (10%), and butyl-*o*-carborane·THF adduct (15%). The overall yield of the reaction was 95%.

Hydroboration of 1-Homoallyl-*o*-carborane with Dicyclohexylborane. To a 25 mL two-necked flask under N_2, at 0 °C, were placed BMS (1.33 mmol, 0.680 mL of a 1.95 *M* solution in THF) and cyclohexene (2.70 mmol, 0.280 mL). The reaction mixture was diluted with THF (3 ml) and allowed to stir at 0 °C for 4 h. To the

dicyclohexylborane (1.30 mmol) was added, at 0 °C, 1-homoallyl-*o*-carborane (1.30 mmol, 260.0 mg) in THF (3 mL). The reaction was permitted to proceed for 12 h at 25 °C. The organoborane was diluted with THF (7 mL) and water (7 mL) and then sodium perborate (5.710 mmol, 878.0 mg) was added. The reaction mixture was allowed to stir at room temperature for 12 h. The two phases were separated and the aqueous phase was extracted with ether (4 x 10 mL). The combined organic phase was washed with NaCl and dried over anhydrous $MgSO_4$. Evaporation of the solvent under low vacuum for 24 h afforded 380.0 mg of semicrystalline material. Dibromobenzene was added (0.150 mmol, 36.5 mg) as an internal standard and ^1H NMR analysis of the product mixture indicated the formation of alcohols in 90% yield. An aliquot of the crude product was treated with 0.4 mL of *N,O*-bis(trimethylsilyl)trifluoro-acetamide containing 1% trimethylchlorosilane. The mixture was heated for 1 h at 30 °C. The resulting TMS derivatives of the alcohols were analyzed by a GC/MS on a 10% carbowax on Chromosorb W column. The ratio of primary to secondary alcohols wsa 99.1:0.9. 4-*o*-Carboranyl-1-butanol: ^1H NMR (acetone-d_6) δ 4.634 (1H, s), 3.500 (2H, t, J = 6.1 Hz), 2.349 (2H, m), 1.552 (2H, m), 1.471 (2H, m); ^{13}C NMR (acetone-d_6) δ 75.7, 61.7, 60.6, 37.0, 31.34, 25.4; ^{11}B (acetone-d_6) δ 0.97 (1B, d), -4.23(1B, d), -7.73(2B, d), -9.52(2B, d), -9.84 (2B, d), -11.12(2B, d).

Hydroboration of 1-Homoallyl-2-methyl-o-carborane with BH_3·THF. To a 25 mL reaction flask, equipped as previously described, was added 1-homoallyl-2-methyl-*o*-carborane (0.952 mmol, 204.0 mg) in tetrahydrofuran (1 mL) followed by BH_3·THF

(0.33 mmol, 0.33 mL of a 1.0 *M* solution). After 3 h at 25 °C, the mixture was cooled to 0 °C and oxidized with sodium perborate (3.713 mmol, 571.3 mg). The crude mixture was diluted with ether (10 mL) and transferred to a separatory funnel. The layers were separated and the aqueous layer was extracted with additional Et_2O (2 x 10 mL). Evaporation of the solvent from the combined organic extracts afforded 215.0 mg of product. ^1H NMR analysis of the reaction produts using dibromobenzene (0.0700 mmol, 16.5 mg) as an internal standard revealed the following: 4-methyl-*o*-carboranyl-1-butanol (73%), 4-methyl-*o*-carboranyl-2-butanol (5%), 1-*n*-butyl-2-methyl-*o*-carborane (12%), and butylcarborane·THF adduct(10%). The latter was isolated by HPLC, and analysis using GC/MS revealed that it was a mixture of 3 isomers. ^{13}C NMR ($CDCl_3$) (major isomer) δ 78.9 (CH), 78.3 (C-R), 74.8 (C-R), 67.8 (CH_2), 35.4 (CH_2), 35.3 (CH_2), 31.5 (CH_2), 29.7 (CH_2), 25.8 (CH_2), and 23.19 (CH_3).

Hydroboration of 1-Homoallyl-2-methyl-*o*-carborane with Dicyclohexylborane. To a 25 mL flask, equipped, as previously described, was added cyclohexene (3.20 mmol, 0.32 mL) followed by BMS (1.60 mmol, 0.810 mL of a 1.98 *M* solution in THF) at 0 °C. The reaction mixture was allowed to stir for 3 h and then 1-homoallyl-2-methyl-*o*-carborane (1.575 mmol, 337.0 mg) in THF (3 mL) was added. The mixture was allowed to stir for 14 h at 25 °C. The organoborane was diluted with THF (10 mL), and H_2O (10 mL) and oxidized with sodium perborate (7.200 mmol, 1,108 mg). The oxidation mixture was heated to 50 °C for 2 h and then cooled to room temperature. The mixture was extracted with ether (5 × 20 mL). The ether extracts

were dried over anhydrous magnesium sulfate to afford after evaporation of the solvent 565.0 mg of an oily product. Analysis by ^{1}H NMR after addition of dibromobenzene (0.100 mmol, 23.5 mg) as internal standard indicated the formation of carborane products in 95% yield. The following distribution was determined: 4-*o*-carboranyl-1-butanol (89%), 1-*n*-(butyl)-2-methyl-*o*-carborane (2%), and radical products of THF and cyclohexyl adducts (9%). The 4-*o*-carboranyl-1-butanol was purified by HPLC (C-18 reverse phase column, 10% H_2O-MeOH): ^{1}H NMR ($CDCl_3$) δ 3.67 (2H, t, J = 6.4 Hz), 2.16 (2H, m), 2.04 (3H, s), 1.66-1.56 (4H, m).

Hydroboration of 1-(4-Pentenyl)-*o*-carborane with BH_3·THF. To a 25 mL flask containing 1-(4-pentenyl)-*o*-carborane (0.891 mmol, 191.0 mg) was added BH_3.THF (0.30 mmol, 0.30 mL of a 1.0 *M* solution). The reaction was maintained at 25 °C for 3 h with stirring. Sodium hydroxide (0.51 mmol, 0.17 mL of a 3.0 *N* solution) and hydrogen peroxide (1.70 mmol, 0.17 mL of a 30 % solution) were added and the reaction was stirred for 10 h at 25 °C. The reaction mixture was extracted with Et_2O (4 x 30 mL). The conbined organic layers were washed with brine, dried over anhydrous $MgSO_4$, and concentrated *in vacuo* to afforded 217.0 mg of a greenish viscous liquid. ^{1}H NMR analysis, using dibromobenzene (0.196 mmol, 46.2 mg) as an internal standard, afforded: 5-*o*-carboranyl-1-pentanol (59%), 5-*o*-carboranyl-2-pentanol (3%), 1-(*n*-pentyl)-*o*-carborane (23%), pentenylcarborane·THF adducts (~8%), and other products (7%). A small amount of *nido* products was also detected. The overall yield was 97%. An aliquot of the dried extract was treated with 0.2 mL of *N,O*-bis(trimethylsilyl)trifluoroacetamide for 30 min at 50 °C.

Analysis by GC/MS indicated a ratio of primary to secondary alcohols of 95:5.

In a separate experiment a solution of 1-(4-pentenyl)-*o*-carborane (1.470 mmol, 315.0 mg) in THF (1 mL) was added to BH_3.THF (0.51 mmol, 0.53 mL of a 0.96 *M* solution), at 25 °C, and allowed to stirr for 2 h. Sodium perborate (2.290 mmol, 351.0 mg) and degassed THF water mixture (10 mL each) were added and the reaction was stirred for 10 h at 25 °C. The reaction mixture was extracted with ether (3 x 30 ml). The combined organic layers were treated with saturated NaCl solution, dried over anhydrous $MgSO_4$, and concentrated *in vacuo* to an oil. Analysis by ^1H NMR using dibromobenzene (0.087 mmol, 20.5 mg) as an internal standard afforded: 5-*o*-carboranyl-1-pentanol (89%), 5-*o*-carboranyl-2-pentanol (6%), 1-(*n*-pentyl)-*o*-carborane (2%), and cage degradation products (3%). The total yield of carborane products was 97%.

Hydroboration of 1-(4-Pentenyl)-*o*-carborane with 9-BBN in Hexanes. To a 25 mL flask containing 5-carboranyl-1-pentene (1.499 mmol, 0.3213 g) was added 9-BBN (1.580 mmol, 3.16 mL, 0.05 *M* in hexanes). The mixture was sonicated at 40 °C for 5 h. The reaction mixture was cooled to 0 °C, and oxidized by the simultaneous addition of sodium hydroxide (4.50 mmol, 1.5 mL of a 3.0 *N* solution) and hydrogen peroxide (15 mmol, 1.5 mL of a 30 % solution). The flask was brought to room temperature and allowed to stir for 12 h. The reaction mixture was extracted with ether (5 x 20 mL). The organic extracts were then dried over $MgSO_4$ and the solvent evaporated *in vacuo* to afford 565 mg of a colorless liquid. ^1H NMR analysis using dibromobenzene as an internal standard (0.146 mmol, 37.0 mg) indicated the

formation of carborane products in 96% yield. Analysis by ^{1}H NMR gave: 5-*o*-carboranyl-1-pentanol (89%), 1-(*n*-pentyl)-*o*-carborane (8%), and a trace of cage degradation products (3%). An aliquot of the crude products was treated with 5 mL of *N,O*-bis(trimethylsilyl)trifluoroacetamide and allowed to stir overnight. Analysis by GC/MS indicated a ratio of primary to secondary alcohols of 100:0. 5-*o*-carboranyl-1-pentanol: ^{1}H NMR($CDCl_3$) δ 3.610 (2H, t, J = 6.4 Hz), 3.542 (1H, s), 2.191 (2H, m), 1.516 (4H, m), 1.329 (2H, m); ^{13}C NMR ($CDCl_3$) δ 75.4, 62.01, 61.10. 37.77, 31.84, 28.86, 24.98; ^{11}B NMR (acetone) δ 1.82(1B, d), -5.05 (1B, d), -8.54 (2B, d), -10.42 (4B, d), -11.90 (2B, d).

Hydroboration of 8-*o*-Carboranyl-1-octene with BH_3·THF. To a 25 ml flask containing a solution of 8-*o*-carboranyl-1-octene (1.391 mmol, 356.6 mg) in benzene (1 mL) was added BH_3·THF (0.510 mmol, 0.49 mL of 0.96 M solution). The reaction mixture was maintained at 25 °C for 4 h with stirring. The flask was then cooled to 0 °C, and the organoboranes were oxidized by the addition of sodium perborate (3.06 mmol, 471 mg) in 10 ml of water. The flask was brought to room temperature and allowed to stir overnight. The reaction mixture was diluted with ether (10 mL), transferred to a separatory funnel and washed with an equal amount of water. The layers were separated and the aqueous layer was extracted with Et_2O (5 x 10 mL). The combined organic layers were dried over anhydrous $MgSO_4$ and concentrated *in vacuo* to afford 0.369 g of an oil. ^{1}H NMR analysis using dibromobenzene (0.140 mmol, 35.6 mg) as an internal standard gave: 1-(*n*-octyl)-*o*-carborane (3%), 8-*o*-carboranyl-1-octanol (87%), 8-*o*-carboranyl-2-octanol (6%), *nido*

products (~1%), and radical products (3%). An aliquot of the dried extracts was treated with 0.3 mL of *N,O* bis(trimethylsilyl)trifluoracetamide with 1% trimethylchlorosilane and heated for 3 h at 30 °C. Analysis of the resulting TMS products by GC/MS revealed a ratio of primary to secondary alcohols of 94:6.

Hydroboration of 8-Carboranyl-1-octene with 9-BBN in Hexanes. To a 25 mL flask containing 8-*o*-carboranyl-1-octene (1.281 mmol, 324.8 mg) was added 9-BBN (1.35 mmol, 2.70 mL, 0.05 *M* in hexanes). The mixture was sonicated at 40 °C for 5 h. The reaction mixture was cooled to 0 °C, and oxidized, by the addition of sodium perborate (8.10 mmol, 1.24 g) and water (15 mL), with vigorous stirring for 8 h. The reaction mixture was extracted with ether (3 × 40 mL). The combined organic extracts were washed with brine, dried over anhydrous $MgSO_4$, and concentrated into an oil. ^1H NMR analysis using dibromobenzene (0.126 mmol, 32 mg) as an internal standard indicated the formation of carborane products in 95% yield. The product distribution was: 1-(*n*-octyl)-*o*-carborane (3%) and 8-*o*-carboranyl-1-octanol (97%). ^{11}B NMR indicated the presence of traces of *nido* products. An aliquot of the dried extract (~20 mm) was treated with 0.3 mL of *N,O*-bis(trimethylsilyl)trifluoracetamide containing 1% trimethylchlorosilane at 30 °C. Analysis of the TMS-ethers using GC/MS indicated a ratio of primary to secondary alcohols of 100:0; <u>8-o-carboranyl-1-octanol:</u> ^1H NMR ($(CD_3)_2CO$) δ 4.661 (1H, s), 3.474 (2H, t, J = 6.8 Hz), 2.313 (2H, m), 1.460 (4H, m), 1.269 (9H, bs); ^{11}B NMR (acetone) δ -1.052 (1B, d), -4.298 (1B,

d), -7.787 (2B, d), -9.627 (4B, d), -11.180 (2B, d); ^{13}C NMR (acetone-d_8) δ 77.11, 63.19, 62.22, 38.11, 33.42, 29.92, 29.77, 29.31, 29.01, 26.32.

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PART II. THE CYCLOADDITION REACTIONS OF METHYL AND (-)-MENTHYL ACRYLATES WITH CYCLOPENTADIENE ON γ-ALUMINA

CHAPTER I

Introduction

Catalysis is the phenomenon in which chemical reactions that occur very slowly, occur rapidly in the presence of a small amount of a substance called a catalyst. In heterogeneous catalysis, the catalyst is usually a solid, and the reactants and products are present in one or more fluid phases (gas or liquid) (1). The heterogeneous reaction takes place on the surface of the solid, and the catalyst provides an alternative mechanistic pathway.

Heterogeneous catalysis has many advantages over homogeneous catalysis: the convenience of separating the desired product of a reaction from the catalyst by filtration; the possible alteration of the reactivity because of strong surface forces; an increase in the reaction yield; and the possibility of altering known reaction pathways by modification of the catalyst characteristics. Despite these advantages, heterogeneous catalysis is often difficult to carry out in practice because the catalyst is easily poisoned since only the atoms on the surface are available for the catalytic reaction.

1.1 *Catalytic Aluminas*

Aluminas have been used extensively in heterogeneous catalysis, particularly in industry, as adsorbents, active catalysts, and catalyst supports (2). Several oxides and mixed oxides, as well as transition metals and noble metals, function as catalysts when supported on alumina (3,4). For example, chromia-

alumina catalysts are used for the conversion of paraffins to olefinic hydrocarbons, molybdena-alumina is used to make toluene and other aromatics from saturated hydrocarbons, and cobalt oxide-molybdenum oxide-alumina is used for hydrodesulfurization, hydrodenitrogenation and hydrocracking reactions (5,6).

As active catalysts, pure aluminas are able to activate hydrogen-hydrogen, carbon-hydrogen, carbon-carbon, carbon-oxygen and oxygen-hydrogen bonds, thus influencing a wide variety of reactions, some of which are summarized in Table 1. The efficiency of the catalyst, is strongly temperature dependent. Thus, H_2-D_2 equilibration reactions take place at very low temperatures, where is the C-H bond activation in exchange and isomerization reactions occur near room temperature, and the C-C bond activation in the skeletal isomerization requires temperatures in excess of 325 °C (2).

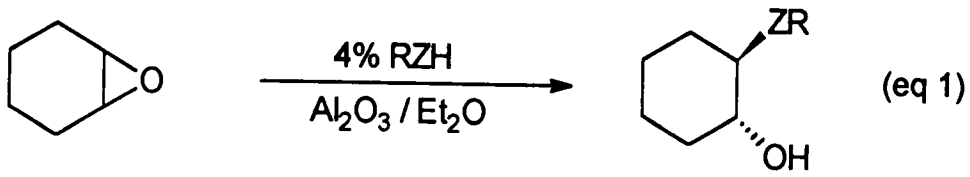
Interest in this area was increased by recent work on organic reactions on chromatographic alumina under unusually mild conditions. For example, Posner *et al.* (7,8) have shown that a wide variety of epoxides, stirred in a slurry of Woelm 200 neutral chromatographic alumina and ethyl ether at 25 °C, were opened by a few equivalents of nucleophilic reagents (eq 1). Thus, alumina impregnated with thiols, alcohols, amines, acetic acid, etc. opened epoxides regioselectively at the less substituted epoxide carbon atom and stereospecifically (*anti*) to give the corresponding β-functionalized alcohols in good yield.

Pagni, Kabalka, *et al.* (9) reported that the bromination of cyclohexene on activated neutral alumina gave *trans*-1-bromo-2-chlorocyclohexane (eq 2). Thus,

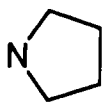
Table 1

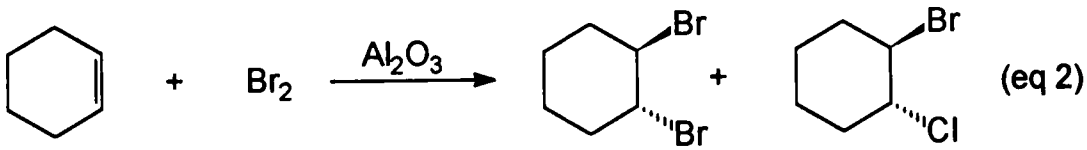
Reactions Catalyzed By Aluminas (2)

	Temperature, K
o-H_2 → p-H_2	78
H_2 + D_2 → 2 HD	150
CH_4/CD_4 isotopic scrambling	300
Alkene + D_2 → alkene-d + HD	300
Benzene + D_2 → benzene-d + HD	300
Double-bond isomerization of	300
Cis/trans isomerization of alkenes	300
Cyclopropane → propene	375
Alcohols → alkenes + H_2O	350
2 Alcohols → ether + H_2O	400
Skeletal isomerization of alkenes	600
o-Xylene isomerization	770



(eq 1)

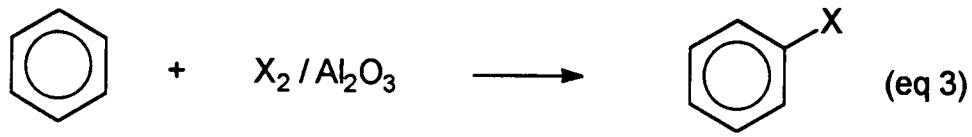
ZR	Yield %
OMe	66
SEt	78
SPh	70
SePh	95
	40



(eq 2)

when bromine impregnated alumina (Br_2/Al_2O_3) was mixed with alkene absorbed alumina in the absence of solvent (Alkene/Al_2O_3), migration of cyclohexene to grains containing immobile bromine and chloride resulted in the formation of a bromonium ion intermediate which underwent reaction with Cl^- to give the observed product. The chlorine in the product arose mainly from the reaction of CCl_4 with the alumina surface, since CCl_4 was used as a solvent to absorb bromine onto alumina. Similar migratory behavior of hydrocarbons on silica gel also has been reported (10). Additional examples (9) of ionic reactions occurring at the surface of alumina impregnated with halogens include the bromination and

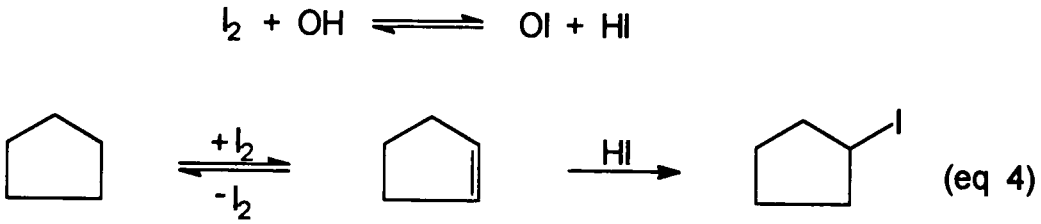
iodination of a series of aromatic substrates at room temperature, a process that is difficult to carry out in solution (eq 3).



(eq 3)

$X_2 = I_2 , Br_2$

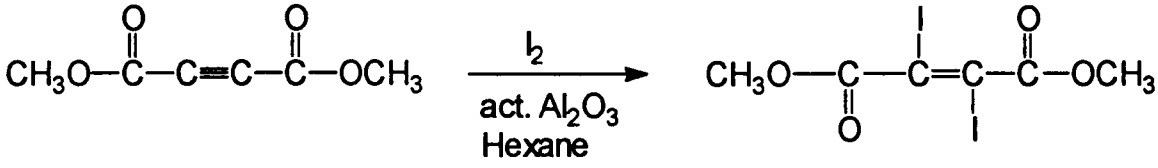
Furthermore, iodine impregnated alumina (I_2/Al_2O_3) reacts with alkenes at <80 °C to yield alkyl iodides (eq 4).



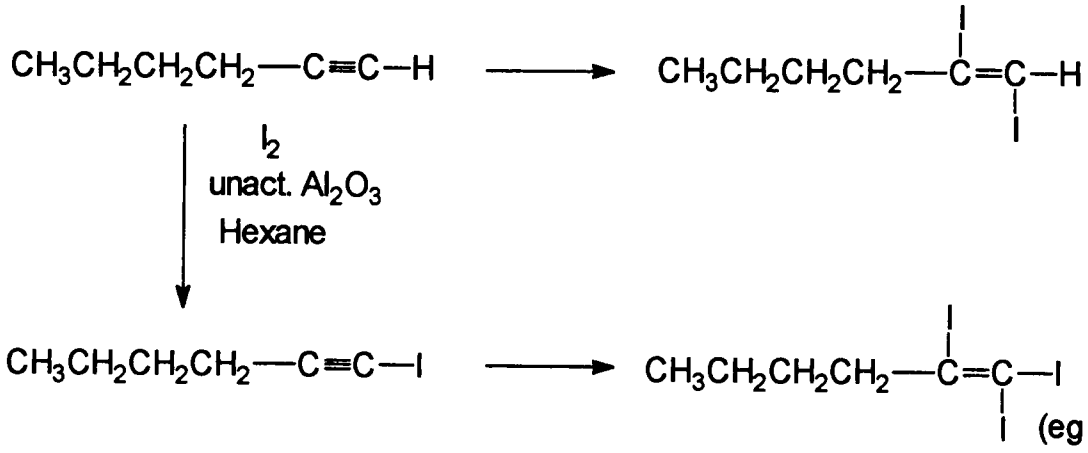
(eq 4)

It was shown that, for I_2/Al_2O_3, there is a positive iodine species that can react with aromatic substrates via electrophilic aromatic substitution and an iodide anion which can react with alkenes. HI is generated in the reaction of iodine with surface hydroxyl groups. In the reaction with alkenes, iodine adds reversibly to the double bond whereas the hydrogen iodide adds irreversibly (9). Alkynes react with I_2 on activated (9), and unactivated (11) alumina in hydrocarbon solvent to

form (*E*)-diiodoalkenes by the stereospecific addition of I_2 to the triple bonds (eq 5). Terminal alkynes on unactivated alumina gave a second minor product, not observed on activated alumina, which was identified as a 1,1,2-triiodo-1-alkene (eq 6). It was determined that the minor product arose from the iodination of a 1-iodoalkynes, formed as an intermediate product (11).



(eq 5)



(eg 6)

1.2 *Preparation and Classification of Aluminas*

Aluminas are formed by dehydration of aluminum hydroxides such as gibbsite, γ-$Al(OH)_3$, bayerite, α-$Al(OH)_3$, and nordstrandite, $Al(OH)_3$, obtained by precipitation from aqueous solutions containing aluminum salts (12). Aluminas exist in several crystalline forms, depending upon the aging method the gelatinous hydroxide and the pyrolysis temperature (4,6,12). The dehydration process gives

alumina its porous nature and thus its high surface area per unit weight. The presence of active sites in pores lead to the solvating effect of alumina and to reactions that normally are not possible on the surface. Commonly, the catalytic properties of aluminas are affected by impurities resulting from the agents used in the formation and aging of the aluminum trihydroxides (4,12,13). Such agents include NH_3(aq), NaOH, ethylene glycol, ethylenediamine, and EDTA.

Aluminas are classified by Lippen (12) based on the temperature at which they are formed.

(a) Low temperature aluminas, the γ-group: $Al_2O_3 \cdot nH_2O$ in which $0<n<0.6$, obtained by dehydration at temperatures not exceeding 600 °C.

(b) High temperature aluminas, called the δ-group: these are nearly anhydrous aluminas and are obtained at dehydration temperatures between 900 °C and 1000 °C.

Alumina types ρ-, χ-, η- belong to group (a) and γ-aluminas κ-, ϑ- and δ-aluminas belong to group (b).

Kirschner, (12) on the other hand, has proposed a classification based upon the crystallographic structures of the aluminas. As these structures are all based on a more or less close-packed oxygen lattice with aluminum ions in the octahedral and tetrahedral interstices, Krischner distinguished three series:

α-series with hexagonal close-packed lattice;

β-series with alternating close-packed lattice; and

γ-series with cubic close packed lattice.

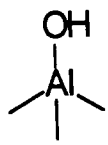
The only member of the α-series is α-alumina. The β-series consists of an alkali or alkaline earth oxide containing β-alumina and χ- and κ-alumina. The γ-series is subdivided into a γ- or low-temperature group, members of which include the γ-and η-alumina, and a δ- or high-temperature group which consists of δ- and ϑ- alumina. Of these different crystalline forms of alumina, only the γ- and η-phases are important catalytically (13-16). The catalytic activity of η-alumina usually higher than that of γ-alumina (17,18). The other main form of alumina, α-alumina, is the most inert of all the aluminum oxides and is used mainly as a catalyst support because of its high-temperature stability (12,18).

1.3 *Structure of γ-Al_2O_3*

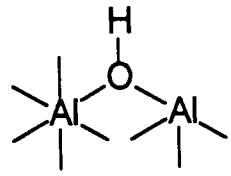
Since a heterogeneous catalytic reaction proceeds on the surface of the catalyst, it is very important to understand the surface and the attacted elements that are responsible for catalytic activity. γ-Al_2O_3 has a defect spinel-type structure comprising a face-centered cubic (fcc) arrangement of 32 oxide ions and a random occupation of 21 1/3 of the 24 available cation sites (12). Unlike the theory of Peri (19) which assumed that only a single crystallographic plane (100) is exposed at the surface of γ-Al_2O_3, Knözinger, et al., (2) developed a theory which assumes that (111), (110), and (100) faces are exposed. Parallel to the (111)-plane which is exposed preferentially in the Knőzinger model, there are two types of oxide layers containing two different cation distributions. The A-layer contains 24 cation positions of which 8 are distributed in octahedral and the

remaining 16 in tetrahedral environments. The B-layer, on the other hand, contains 24 octahedral cation positions.

For the fully hydroxylated surface, which is found on unactivated solid, it is possible to assign relative Brønsted acidities and basicities to these groups based on the nature of their bonding to underlying aluminum cations placed in either tetrahedral or octahedral environments. For the A layer of the (111) face there are two types of OH configurations, one acidic and one basic. In the basic configuration a terminal OH group is coordinated to a single tetrahedral Al^{3+} cation (Type Ia), whereas in the acidic configuration a bridging OH group links a tetrahedral and an octahedral cation (Type IIa). The acidic configuration occur three times as frequently as the basic.



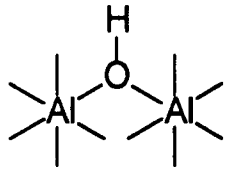
Type Ia



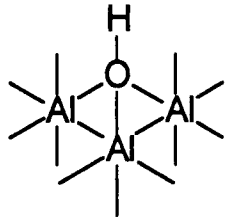
Type IIa

For the B-layer of the (111) face there are also two types of OH group configurations *Type IIb* and *Type III*. The *Type IIb* OH is basic in nature and links two cations in octahedral positions, whereas the *Type III* OH group is acidic in nature, and is coordinated to three cations in octahedral interstices. In this

layer, *Type IIb* configurations occur three times as frequently as the *Type III* configurations.

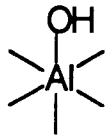


Type IIb



Type III

Similarly, the OH groups in a terminating layer parallel to the (110)-plane can occur either in configuration Ia and IIb or in only one possible configuration, Ib, depending upon their bonding to underlying cations in tetrahedral or octahedral holes. Finally, on top of a layer parallel to the (100)-plane, only *Type Ib* OH configurations can exist.



Type Ib

Based on the above analysis, five different OH configurations are expected on the surface of Al_2O_3. Their actual occurrence and relative concentration depend on the relative contributions of the different crystal faces. This was confirmed by Peri and Hannan (20), who presented infra-red (IR)

spectroscopic evidence for the occurrence of such groups. Thus, when γ-Al_2O_3 was heated to 650-700 °C, the resulting solid had three major hydroxyl stretching frequencies at 3698, 3737, and 3795 cm^{-1} due to isolated hydroxyl groups. In addition, two more bands were seen under high resolution at 3780 cm^{-1} and 3733 cm^{-1} in well dried samples. They also presented IR evidence that active alumina adsorbs water to yield either hydroxyl ions or water molecules, depending upon the temperature of the treatment. Thus, γ-alumina exposed to water vapor at about room temperature absorbs water as undissociated molecules form strong hydrogen bonds to the underlying surface. During the process of activation by heating, water molecules not desorbed from the surface react to form surface hydroxyl groups. Initially, there is a drop in the number of water molecules and an increase in the concentration of hydroxyl groups on the surface. Most water molecules are removed after evacuation at 400 °C. At higher temperatures, the hydroxyl groups are gradually expelled as water but, even at 800 °C to 1000 °C under evacuation, approximately one-tenth of a percent of water still remains on the surface as hydroxyl groups. The number of hydroxyl groups on the surface was determined by measuring the number of hydrogen atoms that could be exchanged with deuterium gas. This showed that the surface is 40% covered with hydroxyl groups after activating at 400 °C, 15% at 600 °C, 2% at 800 °C and 1% above 900 °C.

Table 2 contains a summary of the various hydroxyl configurations, the coordination number of surface anions, and also the net charges on the oxygen

atoms in the oxide ions and hydroxyl groups. The net charge on the hydroxyl groups determines their relative acidities and basicities. These values were obtained as the sum of the negative charge of the anion and the sum of the strength

Table 2

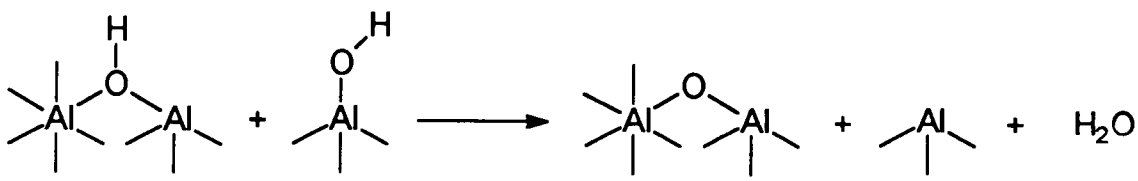
Possible OH Configurations of Alumina

Crystal face	Layer	Configuration	Coordination numbers of surface anion AI(VI)	AI(IV)	Net charge at O	Net charge at OH
(111)	B	III	3	-	-0.5	+0.5
	B	IIb	2	-	-1.0	0
	A	IIa	1	1	-0.75	+0.25
	A	Ia	-	1	-1.25	-0.25
	A,B	Ib	1	-	-1.5	-0.5
(110)		IIb	2	-	-1.0	0
		Ia	-	1	-4.25	-0.25
		Ib	1	-	-1.5	-0.5
(100)		Ib	1	-	-1.5	-0.5

of the electrostatic bonds, (given by the charge of the cation divided by its coordination number) to the anion from adjacent cations. According to Pauling's (21) electrostatic valence rule, the net charge in a stable ionic structure should be equal or nearly equal to zero. Thus, as the net charge on the OH groups decreases, the protonic acidity of the OH groups decreases at the same time that their basicity increases at the same time. The basicity of the OH groups parallels the ease with which they are removed from the surface, since the lower the resulting net positive charge at the anion vacancy, the higher the basicity of the leaving OH group.

1.4 *Surface Dehydration*

According to the model developed by Knözinger, et al. (2), proton acidity and the ease of removal of OH groups should govern the dehydration process, at least in the initial stages at low temperatures. Therefore, ideal behavior requires that one acidic OH group donate a proton to an adjacent basic OH group to form H_2O, which is then driven from the surface.



Type IIa (acidic) *Type Ia* (basic)

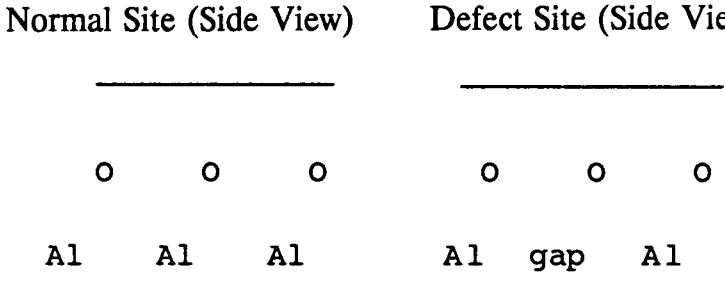
For the (100), face dehydration continues until only isolated OH groups exist, which can no longer react to generate H_2O. For the (111) face, however, normal or ideal dehydration occurs only up to 50% dehydration because, at this point, only acidic OH groups of *Type IIa* remain. This point is reached on activation at 300 °C, which yields 3.65 x 10^{14} normal O^{-2} and Al^{+3} ions per cm^2.

It has been shown, however, that these ions are not involved in most catalytic reactions. Catalytic activity develops only after pretreatment of Al_2O_3 at temperatures higher than 300 °C. It is shown that catalysis of *ortho-para* hydrogen conversion occurs on Al_2O_3 heated above 300 °C and that the rate increased by a factor of 10 corresponding to a steep decrease in surface hydroxyl concentration (2). When the Al_2O_3 is heated above 300 °C, dehydration occurs to yield defect sites on the surface which are known to have enhanced catalytic activity. Such defects are formed by the condensation of equivalent OH groups to give triplet vacancies and neighboring oxide ions (Figure 1). When the solid is heated above 400 °C, so-called *X*-sites are formed which possess even greater catalytic properties although they are fewer in number than normal and defect sites (2). *X*-Sites are poorly understood. It has been shown that an *X*-site must have an exceptional configuration which involves a *Type Ia* OH group. This OH group must be located in an environment where it cannot undergo H-bonding interactions with neighboring anions and must be oriented in such a way that it can be perturbed by an adsorbate molecule coordinated to cations exposed in the neighboring vacancy. A tentative structure for an *X*-site is shown in Figure 2.

It can be concluded from the above analysis that there are no Lewis acid sites on unactivated Al_2O_3, normal Lewis acid and Lewis base sites on Al_2O_3 activated at 300 °C, normal and more active defect sites on Al_2O_3 activated above 300 °C and normal, defect, and highly active *X*-sites on Al_2O_3 activated above 400 °C. Evidence for the presence of the various sites has come from adsorption studies of acid or base sensitive substances. The use of such substances to poison catalytic reactions has unambiguously shown that these acid sites participate in the surface reactions.

It is reasonable to assume then that the high endo selectivity observed in the Diels-Alder reaction of the cyclopentadiene and methyl acrylate on activated alumina is associated with defects sides.

In the (100) face of the activated solid and the (111) face at <50% dehydration the exposed sites consist of alternating oxide anions and aluminum cations. In the defect sites, however, one finds a gap between the aluminum cations in one column of ions and several consecutive oxides in the adjacent column.



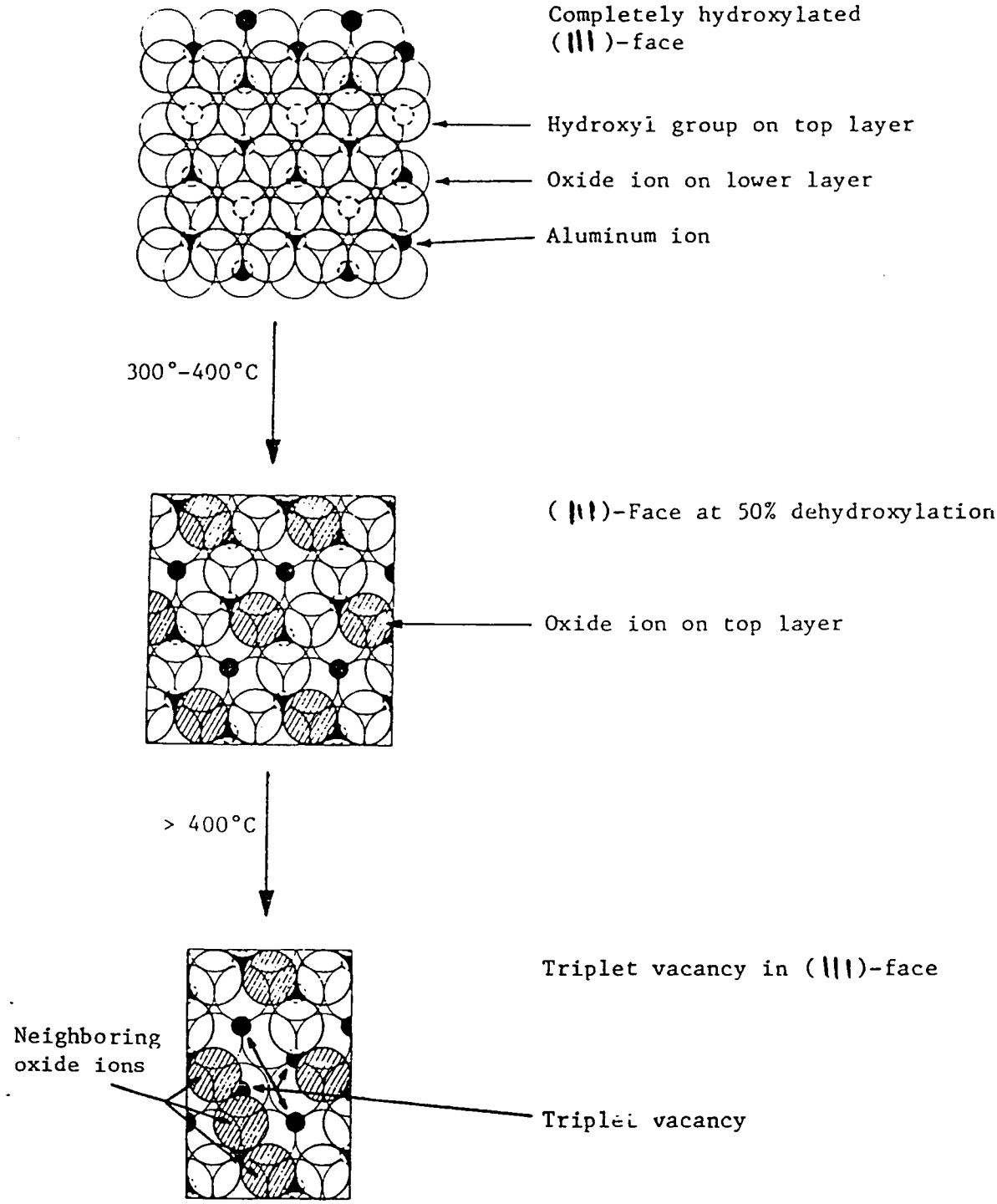


Figure 1. (111)-Face of Aluminum at Different Stages of Dehydration.

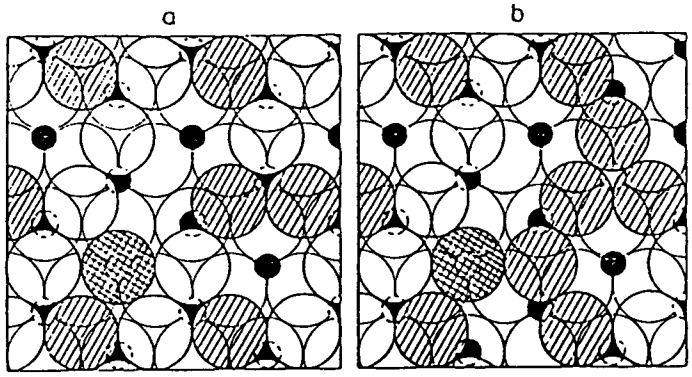


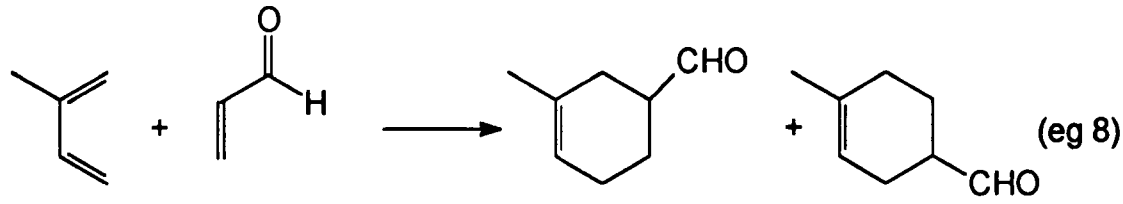
Figure 2. X-Site in (111)-face, A-layer at lower (a) and higher (b) degrees of dehydroxylation: (O) Type IIa hydroxyl groups, (O) oxygen atoms and (O) Type Ia hydroxyl group.

Despite the vast amount of research in this area it is yet not possible to predict how a given solution reaction will occur on a solid. Consequently, a systematic study of well understood solution reactions on surfaces, taking into consideration the properties of the surface, is necessary in order to improve our understanding of the course of such reactions.

1.5 *The Diels-Alder Reaction*

The Diels-Alder reaction (22), or 4+2 cycloaddition reaction, in which a 1,3-diene reacts with an olefinic or acetylenic dienophile to form an adduct with a six-membered hydroaromatic ring is one of the best known organic reactions (eq 7,8).

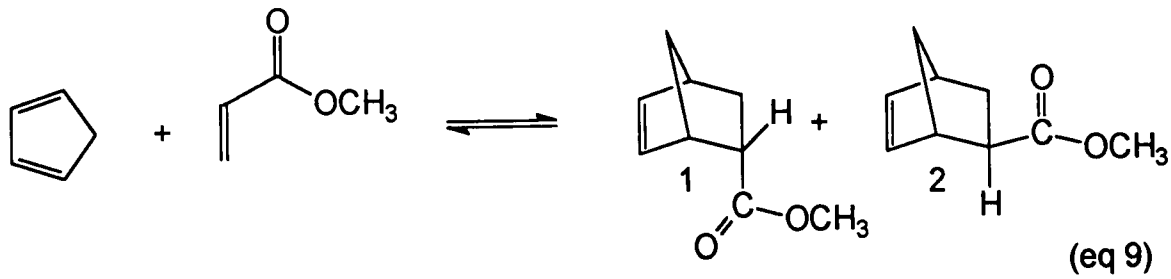
(eq 7)



(eg 8)

meta *para*

In Diels-Alder reactions in which *exo* (*X*) and *endo* (*N*) products are possible, the *endo* adducts are formed preferentially. Berson found (23) that in the reaction of cyclopentadiene with methyl acrylate, the *endo* to *exo* ratio was influenced by the polarity of the solvent (eq 9).



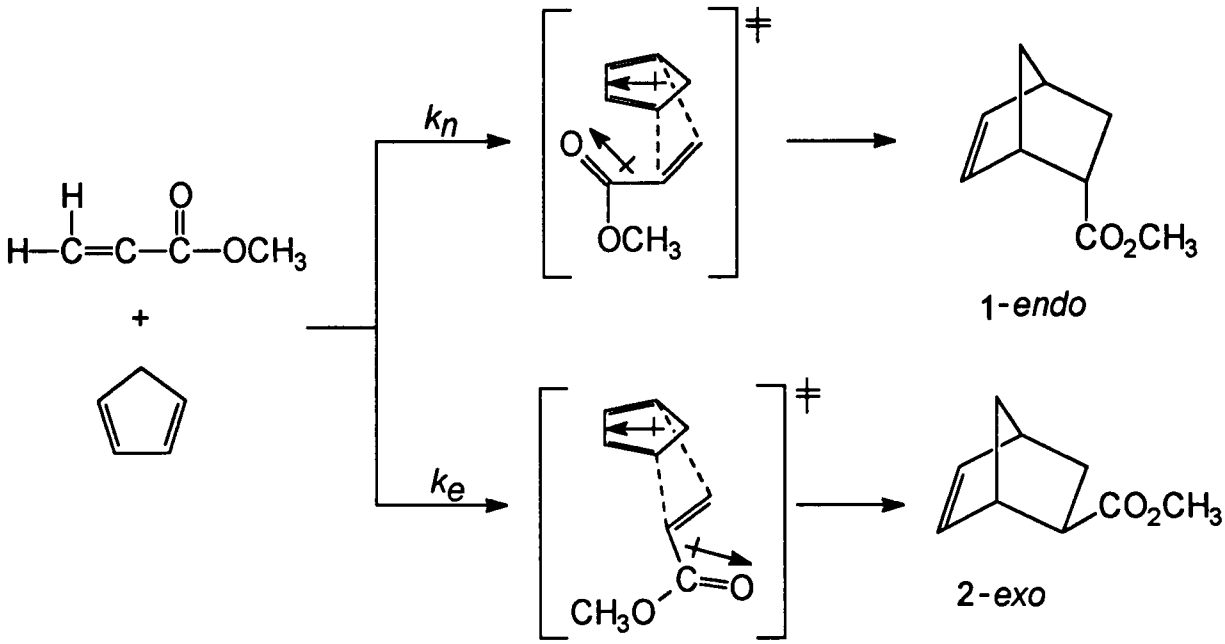
(eq 9)

endo (N) *exo (X)*

Thus, the 78:22 *N/X* ratio of adducts found in benzene increased to 87:13 in the more polar acetic acid. Berson used the *N/X* ratio of the adducts formed in this reaction at 20° C, in a variety of solvents, to establish an Ω scale of solvent polarity, defined as log *N*/log *X* = Ω. The values of Ω at 20 °C lie between 0.445 (triethylamine) and 0.869 (H_2O) and are known for seventeen solvents (24). The increase in Ω corresponds to an increase in the difference of the free energies of activation, $\Delta G_X^{\ddagger}$ -$\Delta G_N^{\ddagger}$, and is readily understandable if it is assumed that the

total dipole moment of the *endo* transition state is greater than that of the *exo* transition state. The resulting better solvation of the *endo* transition state by the more polar solvent lowers the free energy of activation to a greater extent and so leads to preferential *endo* addition (Scheme 1).

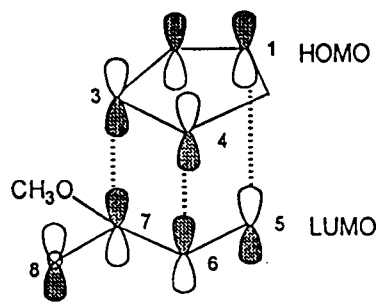
Scheme 1



Sauer and Kredel (25) found that the *endo* to *exo* ratio of adducts, in the addition of methyl acrylate to cyclopentadiene could be significantly changed by addition of Lewis acid catalysts. Thus, $SnCl_4$ and $TiCl_4$ afforded an *N/X* ratio of 95:5, at -70 °C, whereas in the presence of $AlCl_3 \cdot O(C_2H_5)_2$ or $BF_3 \cdot O(C_2H_5)_2$, at -75 °C ≥ 99% *endo* adduct was obtained.

Several explanations have been reported in the literature for the preferred formation of the *endo* adduct. These are, in chronological order: (a) the Alder rule or "maximum accumulation of unsaturation", which predicts that the *endo*

transition state will have a lower energy (26); (b) secondary orbital interactions stabilizing the *endo* transition state (27); (c) geometry constraints favoring the primary orbital overlap for the *endo* transition state (28); (d) attractive van der Waals dispersion forces favoring the *endo* product (29); (e) repulsive forces disfavoring the *exo* product (30); and (f) a combination of steric effects and secondary orbital interactions influencing the stereoselectivity (31). In the recent years the last explanation has been the most popular. Secondary orbital overlap includes the positive overlap of non-bond forming orbitals. For example, in the Diels-Alder reaction of cyclopentadiene with methyl acrylate, carbons 3 and 7 are involved in a secondary interaction since no bond changes occur at these sites. These carbon atoms interact strongly in the *endo* transition state, but not at all in the *exo* transition state. Irrespective of whether the highest occupied molecular orbital (HOMO) of the diene interacts with the lowest unoccupied molecular orbital of the dienophile (LUMO) as is the case shown below, or the reverse, orbital phasing at both the bond forming and secondary centers predicts a stabilizing interaction. Secondary orbital interactions thus preferentially facilitate formation of the *endo* transition state compared with the *exo* transition state where such interactions are absent.

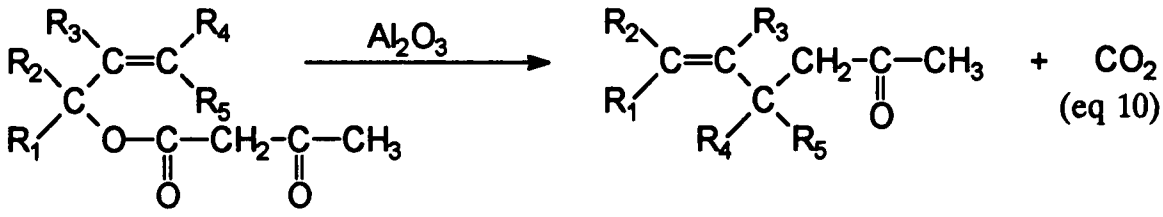


endo

The role of the catalyst in the *endo* selectivity of the Diels-Alder reaction has also received considerable attention. It was shown (32) by means of IR, UV and NMR spectroscopy that the catalyst interacts with the dienophile to form a molecular complex which is stabilized by interaction of the unshared electron pair of the carbonyl oxygen with a low vacant orbital of the catalyst. According to perturbation theory (31), the increase in reactivity of the complexed dienophile is due to the decrease in energy gap between the HOMO of the diene and the LUMO of the dienophile. Thus, in catalyzed Diels-Alder reactions the increase in the reaction rates and *endo* selectivities are a result of an increase in orbital interactions due to a significant rise in electron affinity of the complexed dienophile. In addition to the molecular orbital-based explanation given above, steric hindrance between the methylene group of cyclopentadiene and the dienophile substituents in the transition state of the *exo* adduct has been invoked to interpret the variation of the *endo* to *exo* ratio. Such steric hindrance could be larger in the complexed dienophile thereby making the catalyzed reaction more strongly *endo* selective than the uncatalyzed reaction.

Recently, reports have appeared which describe the Diels-Alder reaction on the surface of solids. Simonyan *et al.* (33) first reported that adsorption of reactants on chromatography adsorbents produces a profound effect on the rate of intramolecular [2+2+1] cycloadditions, a fact also observed in [3,3] sigmatropic rearrangements. Thus the rearrangement of several allyl acetoacetates at 25° C on Al_2O_3 occurred rapidly (30 min) to give γ-δ unsaturated ketones in high yields

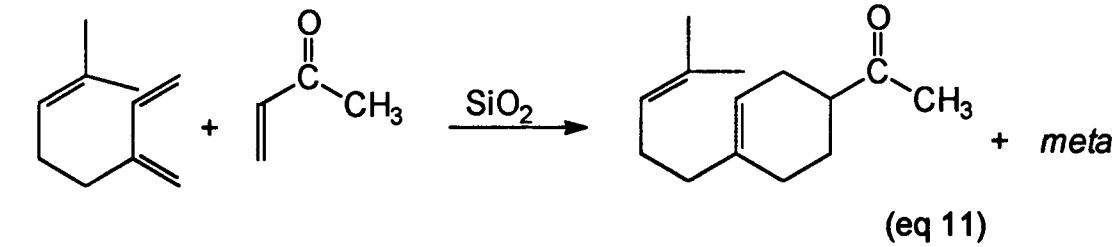
(85-90%) (eq 10). These conditions were considerably milder than those used in solution in the absence of Al_2O_3 (160-200 °C for 3-6 h, 40-70% yield).



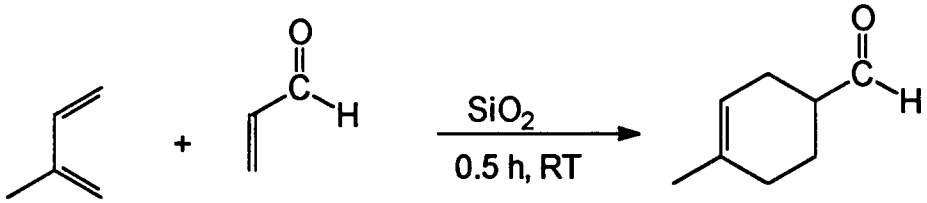
(eq 10)

Furthermore, Veselovsky (34) reported that, when an equimolar mixture of myrcene and methyl vinyl ketone was heated on chromatographic grade silica gel at 50 °C for 5 h in the absence of solvent (dry method), the anticipated Diels-Alder adduct was formed in 70% yield (eq 11). These conditions again were much milder than those using uncatalyzed liquid phase conditions (140 °C, 5 h). On silica gel activated at 200 °C, the reaction afforded the Diels-Alder adduct in close to 100% yield within 1 h at 20 °C. The reaction was also significantly influenced by the loading of reagents on the silica. Thus on 200 °C activated SiO_2, a nearly 100% yield was achieved for a ratio of SiO_2 : reactants ranging from 10 to 20:1 (w/w) while, with a ratio of 2:1 or 50:1, the conversion dropped to 10-50%. The use of the dry method also resulted in an improved regioselectivity. Thus, the reaction of myrcene with methyl vinyl ketone on silica gel afforded the *para* and *meta* adducts in a 97:3 ratio, as opposed to a 83:17 ratio obtained in solution. Similar results (34) were observed in the cycloaddition

reactions of a variety of alkenes with acrolein, methyl acrylate , and crotonaldehyde (eq 12-14) on silica gel at room temperature.

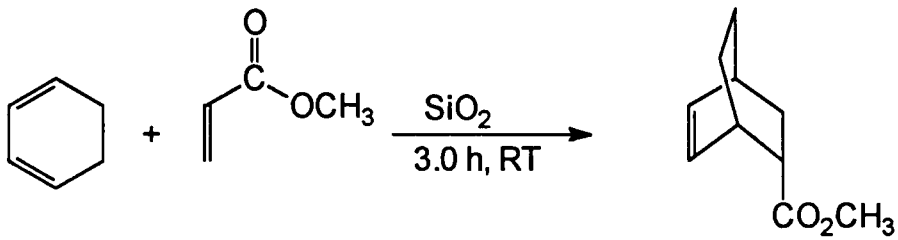


(eq 11)



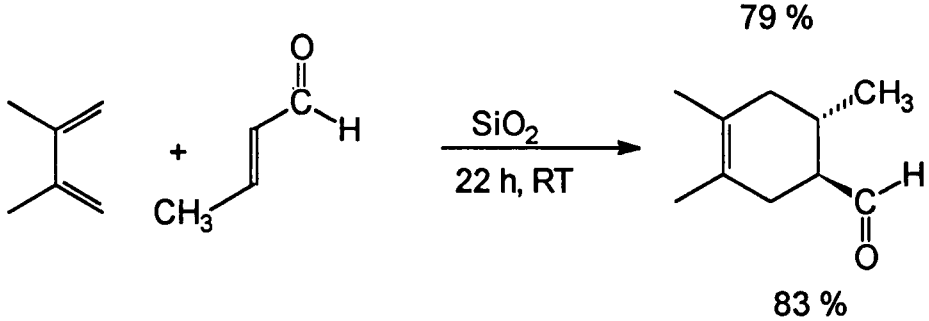
(eq 12)

70 %



(eq 13)

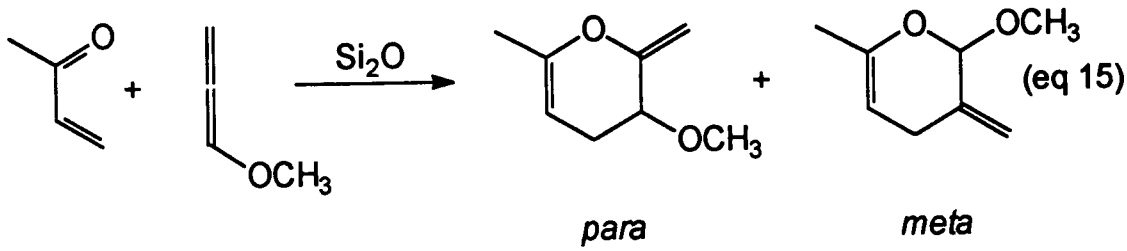
79 %



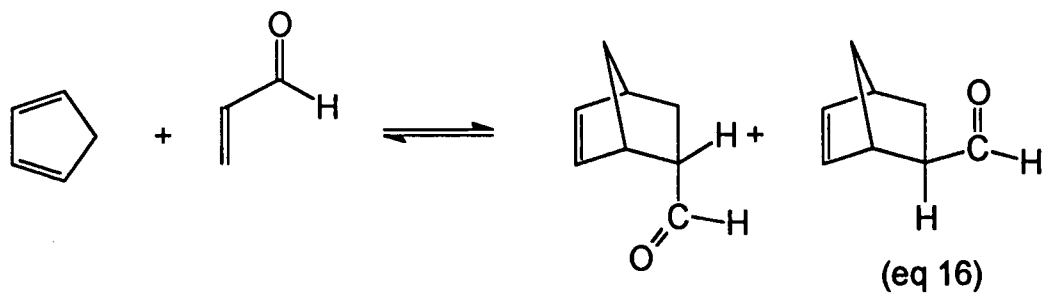
(eq 14)

83 %

The dry method was also used successfully in the inverse-type, hetero-Diels-Alder reactions (40), particularly in cases where several Lewis acid catalysts, (ZnI_2, $Et_2O \cdot BF_3$, $EtAlCl_2$, $Cu(OAc)_2$) had failed. For example, under dry conditions on silica gel, methacrolein and 1-methoxy-1,2-propadiene reacted 50 times faster under dry conditions on silica gel than in solution (eq 15). The selectivity of the reaction was also improved from 86:14 obtained in solution to 91:9 under dry conditions.



Parlar and Baumann (36) have also reported the Diels-Alder reaction of cyclopentadiene and several dienophiles occurring on a variety of solids. In a few cases, the stereoselectivity of the surface reaction was considerably different from that for the corresponding solution reaction. For example, in the reaction of cyclopentadiene with acrolein on non-activated neutral Al_2O_3 they reported an *endo* to *exo* ratio of 1:1 (eq 16) whereas the corresponding ratio in solution is 3:1.



Furthermore, a dramatic increase in the *endo* to *exo* ratio from 3:1 in solution to 30:1 on Al_2O_3 was observed in the reaction of cyclopentadiene with methyl acrylate.

Parlar and Baumann also reported that the *endo* to *exo* ratio of adducts was invariant whether activated or unactivated Al_2O_3 was used, and that in addition, the temperature of the reaction (40-70 °C) was inconsequential. Since the surface of out-of-the-bottle and activated Al_2O_3 is different, the invariance of the *endo* to *exo* ratio to the nature of the solid is quite unexpected and requires further investigation.

1.6 *Statement of the Problem*

A detailed study of the Diels-Alder reaction on Al_2O_3 would be very informative, because, as it was discussed in section one, the reaction is Lewis acid catalyzed and dehydrated Al_2O_3 is a potent Lewis acid. If the *endo* to *exo* ratio were sensitive to the Al_2O_3 activation, it could be used to measure the activity of Al_2O_3 activated under a variety of conditions. The goals of this investigation were to examine the Diels-Alder reaction in heterogenous media and to use the reaction as a probe to understanding the nature of the Al_2O_3 surface.

CHAPTER II

The Reaction of Methyl Acrylate and Cyclopentadiene on γ - Al_2O_3

The Diels-Alder reaction on the surface of alumina can be run either by adsorption of one addend to the solid and then addition of the other addend in a solvent or, alternatively, the addends can be adsorbed on separate batches of the solid with a subsequent mixing of the two powders. The latter method requires an intergranular hopping of one or both of the addends for the reaction to occur. In the present study, methyl acrylate (MA) was adsorbed on the solid and then an equimolar amount of liquid cyclopentadiene (CP) was slowly added to the solid at 0 °C via a syringe. This method was necessary because cyclopentadiene easily dimerizes on the solid, even at 0 °C. The mixture was then heated at 50 ° C for 5 h with continuous stirring.

2.1 *Results on Unactivated Alumina*

The Diels-Alder reaction of cyclopentadiene with methyl acrylate was initially studied on unactivated, out-of-the-bottle Al_2O_3. Different weights of Al_2O_3 to a given weight of methyl acrylate and cyclopentadiene (7.55 mmol each) were used. After completion of the reaction, the yields of adducts and *endo:exo* ratios were determined. The results are summarized in Table 3. The ratios were determined by GC analysis on a 9% carbowax column, oven temperature 120 °C (5 min), 10° C/min, 180 °C (2 min). The *exo* isomer eluted at 14.1 min and the *endo* isomer at 14.9 min. This was confirmed by separation of the adducts using

preparative GC on a 30% carbowax column maintained at 185 °C and comparison of their ^{13}C and ^{1}H NMR spectra with literature data (42). The *endo* to *exo* ratio was also determined by ^{1}H NMR spectroscopy. Integration of the methoxy signals due to the *exo* and *endo* adducts at 3.63 ppm and 3.57 ppm, respectively, afforded ratios which were within ±1% of those obtained by GC analysis. The mass spectra of the *endo* and *exo* isomers were identical; they each showed a molecular ion at 152 m/e and a base peak at 66 m/e due to the cyclopentadiene ion fragment. The results are presented in Table 3.

The data clearly show that the cycloaddition reaction occurs on the surface of the solid and that the loading of reagents on Al_2O_3 has a significant effect on the diastereoselectivity of the reaction. When the weight to weight ratio of Al_2O_3 to reagents is 0.03 (entry 1), a 2.9 ratio of *endo* to *exo* adducts is obtained. This is very close to the 2.1 *endo*: *exo* ratio observed when the reaction is run neat. The small difference in the *endo* to *exo* ratios, in the solid reaction, is attributed to the presence of Al_2O_3, since Al_2O_3 influences only a small fraction of the reaction before it loses its effect. The bulk of the reaction is occurring in the liquid phase. The same explanation can be given for reactions run with w:w ratios up to 0.4 (entries 1-4). Furthermore, Table 3 shows that, when the weight to weight ratio of Al_2O_3 to reagents is 5.0 or greater, (entries 4-7) the diastereoselectivity of the reaction increases significantly, reaching a maximum *endo*: *exo* ratio of 5.8 when the w:w ratio is 10:1. Obviously, as the amount of Al_2O_3 increases, so does the fraction of the reaction occurring near or at the

Table 3

The Effect of Surface Loading on the *Endo* to *Exo* Ratio
Using Unactivated Al_2O_3

Entry	(w:w)[b] Al_2O_3:(CP+MA)[a]	*Endo:Exo*	%Yield
1	.03	2.9	54
2	.05	2.9	57
3	.10	3.0	53
4	.40	2.8	55
5	4.0	4.5	60
6	5.0	4.2	57
7	10.0	5.8	62

[a]CP+MA = equimolar amounts of cyclopentadiene + methyl acrylate.
[b]Weight to weight ratio.
[c]Isolated.

surface. As was discussed earlier, unactivated Al_2O_3 does not have Lewis acid sites exposed on the surface. Therefore, the *endo* to *exo* ratios should not have changed as the w:w ratio was altered and should have been similar to those found in solution. This is not the case, however, because unactivated Al_2O_3 at room temperature contains undissociated water held with strong hydrogen bonds to the

underlying surface (18). Thus, the diastereoselectivity of the reaction in this case must be affected by the polar environment of the surface and not by exposed aluminum ions. Indeed, by measuring the *endo* to *exo* ratio for the reaction of cyclopentadiene with methyl acrylate at 20° C, 10:1 w/w ratio Al_2O_3 : (CP+MA), the Ω value was found to be 0.740. The surface of out-of-the-bottle alumina is thus more polar than ethanol (Ω = 0.718) but less polar than water (Ω = 0.825).

2.2 *Results on Dehydrated Alumina*

A series of reactions were run on dehydrated Al_2O_3 prepared by heating activity 1 neutral Al_2O_3 at different temperatures for 4 hours under vacuum. Two loadings of cyclopentadiene and methyl acrylate were used on each activated Al_2O_3 and the *endo* to *exo* ratio of adducts was measured in each case. The results are summarized in Table 4.

The results show the same general trend with both loadings, but the effect is considerably more pronounced with the lower loading. Thus, for the 10:1 w:w loading, the *endo* to *exo* ratio of 5.8 on unactivated Al_2O_3 rises slowly to 10.3 on Al_2O_3 activated at 300 °C and then rises sharply to a value of 52 on Al_2O_3 activated at 400 °C. These data show that, even with activated Al_2O_3, the loading of cyclopentadiene and methyl acrylate influences the diastereoselectivity significantly. Since the reaction occurs at the surface of the solid, less than one monolayer of coverage is necessary for the Al_2O_3 to exert its maximum catalytic effect. The Al_2O_3 employed in this work had a surface area of 155 m^2/g. A monolayer coverage of cyclopentadiene was thus calculated to be 1.62 mmol/g

Table 4

Diastereoselectivity Observed in the Reaction of CP With MA on Al_2O_3 of Varying Activity.

Activation Temperature	Al_2O_3:(MA+CP) (w:w) *Endo:Exo*	
	5:1[a]	10:1[b]
Unactivated	4.5	5.8
200°	5.0	7.0
300°	6.8	10.3
400°	40	52

[a]5.76g of Al_2O_3 to 7.55 mmol of CP and MA each.
[b]11.52g of Al_2O_3 to 7.55 mmol of CP and MA each.

Al_2O_3, whereas the monolayer coverage of methyl acrylate corresponded to 1.56 mmol/g Al_2O_3. Thus, the 5:1 w/w loading corresponds to slightly greater than a monolayer coverage, whereas the 10:1 loading corresponds to less than a monolayer coverage. The modest increase in the *endo* to *exo* ratio on Al_2O_3 activated up to temperatures of 300 °C is probably due to a small increase in the polarity of the surface as approximately 50% of chemisorbed water molecules are being replaced by an equal number of Al^{3+} and O^{2-} ions. As Al_2O_3 ions are exposed under these conditions, some of the increase in selectivity must also be due to a contribution from a Lewis acid-catalyzed Diels-Alder reaction. On 400 °C Al_2O_3, the sharp increase in the *endo* to *exo* ratio from 10.3 to 52 is too large to be due to an analogous increase in the polarity of the solid. Peri (19) has shown that the surface of Al_2O_3 activated at this temperature consists of 40% hydroxyls and, by inference, 30% each of exposed Al^{3+} and O^{2-} ions. Thus it has to be concluded that, on Al_2O_3 activated above 300 °C, catalytic sites are being created which influence the *endo* selectivity significantly.

The overall yields of the *endo* and *exo* adducts on both activated and unactivated Al_2O_3 were not very high. This is mainly due to a competitive dimerization of the cyclopentadiene, which eliminates one of the reagents. In some instances loss of adducts also resulted from irreversible adsorption on the solid. Increases in the weights of the solids of up to 30% have been observed. Examination of the solid by IR after careful extraction and drying has shown an intense broad absorption band at 1554 cm^{-1}. Lappert (40) has shown that the

normal 1720 cm^{-1} carbonyl band of methyl esters is shifted to 1560-1640 cm^{-1} by the presence of Lewis acid catalysts.

When the cycloaddition reaction of cyclopentadiene with methyl acrylate was run on 400 °C-Al_2O_3 at various reaction times, the results shown in Table 5 were obtained. Table 5 shows a modest increase in yield of product with time, whereas the *endo* to *exo* ratio remains essentially unchanged.

Table 5

Ratio of *Endo:Exo* Adducts as a Function of Time[a]

Reaction Time (hr)	% Yields[b] of Adducts	*Endo:Exo*
0.5	53	55
1.0	56	57
2.0	55	48
5.0	62	52

[a] The weight ratio of Al_2O_3 to equimolar cyclopentadiene and methyl acrylate was 10.
[b] Isolated.

CHAPTER III

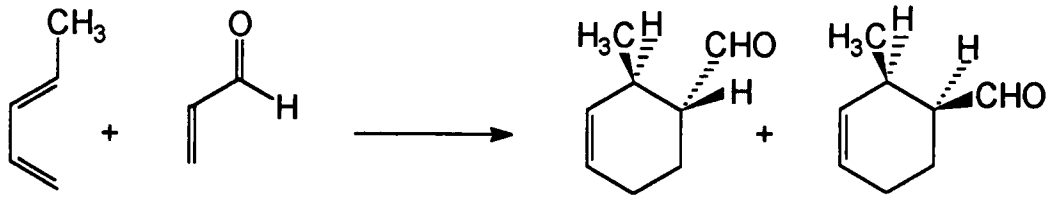
The Epimerization of the Exo- to Endo-Adducts

In order to evaluate the causes of the dramatic increase in the *endo: exo* ratio of adducts in the cycloaddition reaction of methyl acrylate with cyclopentadiene on activated Al_2O_3, the role of epimerization of the *endo* and *exo* adducts was examined.

Epimerization of Diels-Alder adducts is usually not observed at room temperature. More vigorous reaction conditions and strong base or acid is needed to initiate conversion of the *endo* adduct to the more stable *exo* isomer (41-45). Nevertheless, several Lewis acid-catalyzed epimerization reactions occurring at room temperature have recently been reported (46).

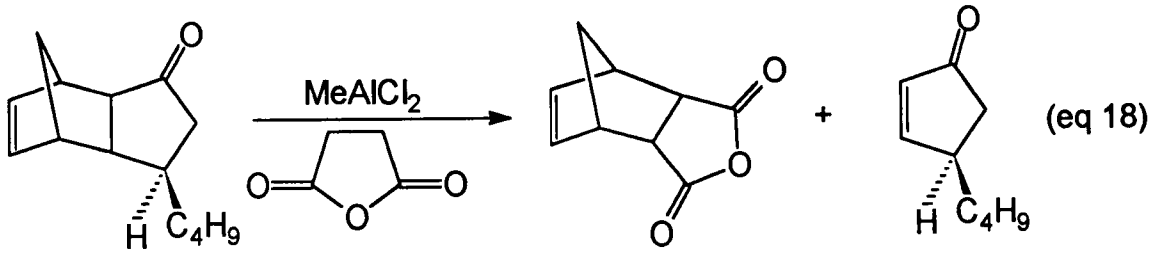
Güner (45) noted the rapid epimerization of the *exo* and *endo* adducts formed in the reaction between *trans*-1,3-pentadiene and a series of dienophiles at room temperature in the presence of $BF_3 \cdot Et_2O$. For example, the uncatalyzed cycloaddition of *trans*-1,3-pentadiene with acrolein afforded an *endo:exo* ratio of 85:15 after 6 days at room temperature (eq 17). An *endo:exo* ratio of 63:37, which is the equilibrium composition, was observed after 30 days at room temperature. In the presence of the catalyst, however, the kinetically controlled ratio could not be determined because of rapid epimerization. The equilibrium *endo:exo* ratio of 63:37 was obtained in 25 min. Similar results were obtained with the dienophiles methyl vinyl ketone and methyl acrylate, but the rates of epimerization were much

slower. It was postulated that the epimerization proceeded by an enol intermediate which was substantially stabilized by the Lewis acid catalyst (45).



	endo		*exo*	
Al_2O_3 / 6 Days	85	:	15	
Al_2O_3 / 30 Days	65	:	35	(eg 17)
$BF_3(OEt)_2$ / 25 Min	65	:	35	

Grieco *et.al* (46), reported several Lewis acid-catalyzed retro-Diels-Alder reactions. For example, when *exo*-3-butyl-tricyclo[5.2.1.$0^{2,6}$]dec-8-en-5-one was treated at ambient temperature with 1.1 equivalent of methylaluminum dichloride in the presence of maleic anhydride, to trap the formed cyclopentadiene, 4-butylcyclopent-2-enone was obtained in an 80% yield (eq 18).



(eq 18)

Since activated Al_2O_3 possesses acid and base sites, it is possible that they could catalyze epimerization reactions by either or both of the previously mentioned pathways (via enol/enolate or reversible Diels-Alder reaction).

3.1 *Results on Unactivated and 400 °C Activated Al_2O_3*

Control experiments showed that epimerization reactions took place on both 400°-Al_2O_3 and unactivated-Al_2O_3. Thus when the pure *exo* adduct, isolated by preparative GC on a 30% carbowax column, was adsorbed on 400 °C activated alumina, w:w Al_2O_3:(CP+MA) 10:1, the reaction yielded 10% of the *endo* adduct after heating at 60 °C for 24 h, whereas the *endo* adduct isolated in the same manner did not epimerize under similar conditions. The recovery of the esters from alumina extracted with ether several times was 70% and 75%, respectively. When the above reaction was repeated on out-of-the-bottle alumina, pure *exo* adduct yielded ~2% of the *endo* adduct after heating at 60 °C for 24 h, whereas the *endo* adduct did not epimerize. Furthermore, the *exo* adduct on both solids was shown by GC analysis on a 10% carbowax column to undergo a slow hydrolysis reaction to the corresponding acid (3-5%). The epimerization of the *exo* to *endo* adduct is rather unusual because epimerization reactions in this system normally occur in favor of the thermodynamically more stable *exo* products.

3.2 *Results on Alumina Activated at 800 °C*

The alumina used in this series of experiments was prepared by heating activity 1 neutral alumina at 800 °C in an electric oven under an argon atmosphere. When equimolar amounts (7.55 mmol) of cyclopentadiene and methyl acrylate were mixed at room temperature on 800°-Al_2O_3, with a weight to weight ratio of alumina to reagents of 15:1, the results summarized in Table 6 were obtained.

Table 6

Effect of 800°-Al_2O_3 on the *Endo:Exo* Ratio in the Reaction of CP and MA at 25 °C

Reaction Time	*Endo:Exo*[a]
5 h	49:51
24 h	48:52
48 h	46:54

a) Determined by GC and ^{1}H NMR spectroscopic analyses.

The results show that the product ratio is essentially invariant as a function of time on 800°-Al_2O_3 and is quite different than observed on less activated Al_2O_3. Based on the earlier described results and the presence of defect and *X*-sites on the 800°-solid, a very large *endo:exo* ratio would have been predicted. Instead an *endo:exo* ratio of nearly one was obtained which probably represents the equilibrium constant for the *endo* to *exo* interconversion under these conditions. Furthermore, when 7.50 mmol of a 93:7 mixture of *endo:exo* ester adducts was subjected to 24 g of Al_2O_3 activated at 800 °C an equilibrium *endo:exo* ratio of

43:57 was obtained within 5 h at room temperature (Table 7). This ratio was also shown to be invariant to changes in reaction time or temperature.

Table 7

The Effect of 800°-Al_2O_3 on the
Rate of Epimerization of CP + MA Adduct[a]

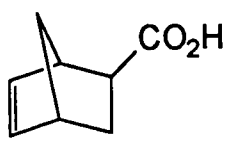
Time (h)	Temp °C	*Endo:Exo*
0	25	93:7
5	25	43:57
24	25	46:54
48	60	46:54

[a] Al_2O_3:(CP + MA adduct), w/w = 15:1.

Additional experiments demonstrated that the rate of epimerization on 800 °C Al_2O_3 is influenced by the weight to weight ratio of Al_2O_3:(adduct). Thus, when pure *endo* adduct was treated with Al_2O_3 activated at 800 °C, with a weight to weight ratio of alumina to endo adduct of 10:1, the results summarized in Table 8 were obtained.

The *endo:exo* ratios reported in column 3, Table 8, were obtained by GC/MS analysis of the ester adducts (**1** + **2**) extracted from the solid with ether. In all reactions but one, the carbomethoxy esters were recovered free from any contaminants. In the reaction conducted at 80 °C, however, a mixture of *endo* and *exo* acids **3** was also recovered, in 13% yield, as evidenced by GC/MS analysis.

When the Al_2O_3 was dissolved in concentrated HCl (column 4, Table 8), GC/MS analysis of the products recovered, revealed the presence of hydrolysis products, some of which had undergone rearrangement to lactones (**4-6**). The



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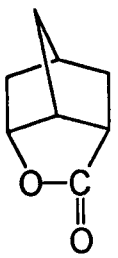

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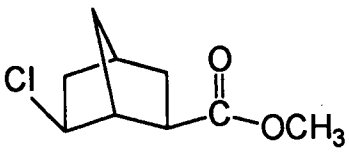

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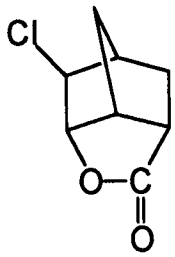

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Table 8

The Effect of 800°-Al_2O_3 on the Epimerization of Pure *Endo* adduct (**1**) [a]

Reaction Temp (°C)	Reaction Time (h)	*Endo:Exo*	Recovery (%)[b]	(%)[c]	(%)Total Yield
3	3	74:26	81	7	88
56	3	75:25	74	18	95
65	1	73:27	66	23	89
80	24	70:30	50	20	83

[a] Al_2O_3:*Endo*, w/w = 10:1
[b] Esters extracted from Al_2O_3 into ethyl ether
[c] Additional products extracted after dissolution of Al_2O_3 in conc. HCl.

identity of **3** was assigned based on comparison of its GC/MS spectrum with authentic material. The identities of the remaining compounds, however, are tentative and are based on their GC/MS fragmentation patterns (Table 9). It is well known that norbornene derivatives can undergo facile rearrangements in acidic media. Thus the compounds postulated above are those of the expected major isomers.

Table 9

The Important Peaks in the Mass Spectra of Adducts Obtained by Dissolution of Al_2O_3 in HCl

	m/e (% of base peak)							
	M^+	$M^+ + 2$	Base 100%	2nd	3rd	4th	5th	6th
3	138		66	91(8)	67(7)	77(6)	93(3)	
4	138		6	79(63)	110(46)	81(25)	93(13)	95(11)
5	186(2)	185(5)	66	87(71)	67(57)	93(41)	115(28)	153(18)
6	176(6)	174(2)	66	66(98)	93(48)	91(23)	79(19)	138(12)

In a control experiment, a mixture of the carbomethoxy esters **1** and **2** in ether was treated with concentrated HCl for 30 min. Analysis of the products by GC/MS afforded a mixture of isomeric chloro esters of which **5** was the major component. In a separate experiment, a mixture of the esters was adsorbed on 800°-Al_2O_3 for 30 min and then the alumina was treated with acid for 1.5 h.

Extraction with ether afforded, by GC/MS analysis, a mixture of products of which the major components were: **3** (2%), **4** (7%), **5** (84%), and **6** (5%). These results clearly indicate that the reaction of CP with MA on the 800°-Al_2O_3 generates additional products besides the expected carbomethoxy esters, which adhere strongly to the solid and can be recovered, although rearranged, upon treatment of alumina with HCl. In yet another experiment, a mixture of acid **3** in a ± 70:30 *endo:exo* ratio was treated with 800°-Al_2O_3, (Al_2O_3:(**3**) = 10:1, w/w), for four hours at 65 °C. When the solid was extracted several times with ethyl ether, only **3** was recovered (50%) which was contaminated with a trace amount of **4** (~2%). Analysis, by GC/MS, of the recovered **3** indicated that the *endo:exo* ratio was unchanged. An additional 32% of products was recovered by dissolving the alumina in concentrated HCl. Analysis of this mixture by GC/MS indicated the presence of **3** (32%), **4** (22%), and **6** (46%). These results support the hypothesis that the carbomethoxy esters undergo partial hydrolysis to the corresponding acids catalyzed by the 800°-Al_2O_3. Furthermore, the rearrangement of the acids to the corresponding lactones appears to occur more readily in the presence of HCl, although 800°-Al_2O_3 also appears to catalyze this reaction but at a slower rate. Thus, these results clearly demonstate that it is not possible to measure the equilibrium constant for the interconversion of the *endo* and *exo* esters on the 800°-Al_2O_3 despite the facility of this reaction.

3.3 *Mechanism of Epimerization*

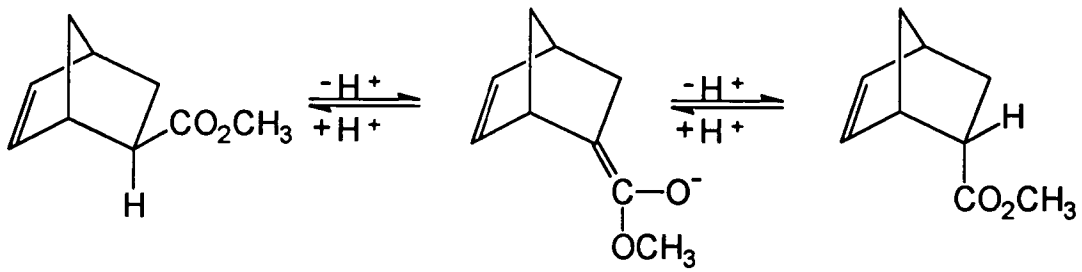
As it was pointed out earlier, the epimerization of the *exo* and *endo* esters could occur by two reasonable mechanisms, one proceeding through an enolate intermediate and the other via the retro-Diels-Alder reaction of *endo* and *exo* adducts. In the first pathway, an exposed O^{-2} ion would abstract the *endo* hydrogen at carbon-2 of the *exo* adduct to yield an enolate which, on protonation by a surface hydroxyl from the less sterically hindered *exo* face will generate the *endo* adduct. This mechanism could easily be tested if the O-H groups on alumina were replaced by O-D. If the enolate pathway were correct, the substrates would incorporate deuterium at C-2. Deuterated alumina in fact is known. Kabalka and Pagni (47) prepared this material and showed it to be an excellent medium on which to replace the acidic hydrogens of substrates with deuterium under mild conditions. Phenylacetylene, for example, was deuterated at the terminal position (up to 99%) when stirred in pentanes with highly deuterated alumina for 16-18 h at room temperature.

In this work, the alumina was deuterated by driving off the hydrogen as H_2O at 400 °C under vacuum and then rehydrating by addition of 2 g of D_2O. This process was repeated five times. Analysis of the ejected H_2O/D_2O mixture by ^1H NMR using tetramethylammonium bromide as an internal standard indicated that the alumina was >96% deuterated. However, when the *endo* adduct was treated with the above alumina at 60 °C for 24 h, recovered *endo* ester contained no deuterium as evidenced by mass spectral analysis. The molecular

ion of the adduct was detected at 152 m/e and the M+1 peak, whose intensity is indicative of deuterium incorporation, was 10% of the M^+ peak, as expected for a non-deuterated substrate (47,64). When the *exo* adduct was treated in a similar manner, neither the formed *endo* adduct nor the recovered *exo* adduct contained deuterium. These results ruled out the enolate mechanism (Scheme 2).

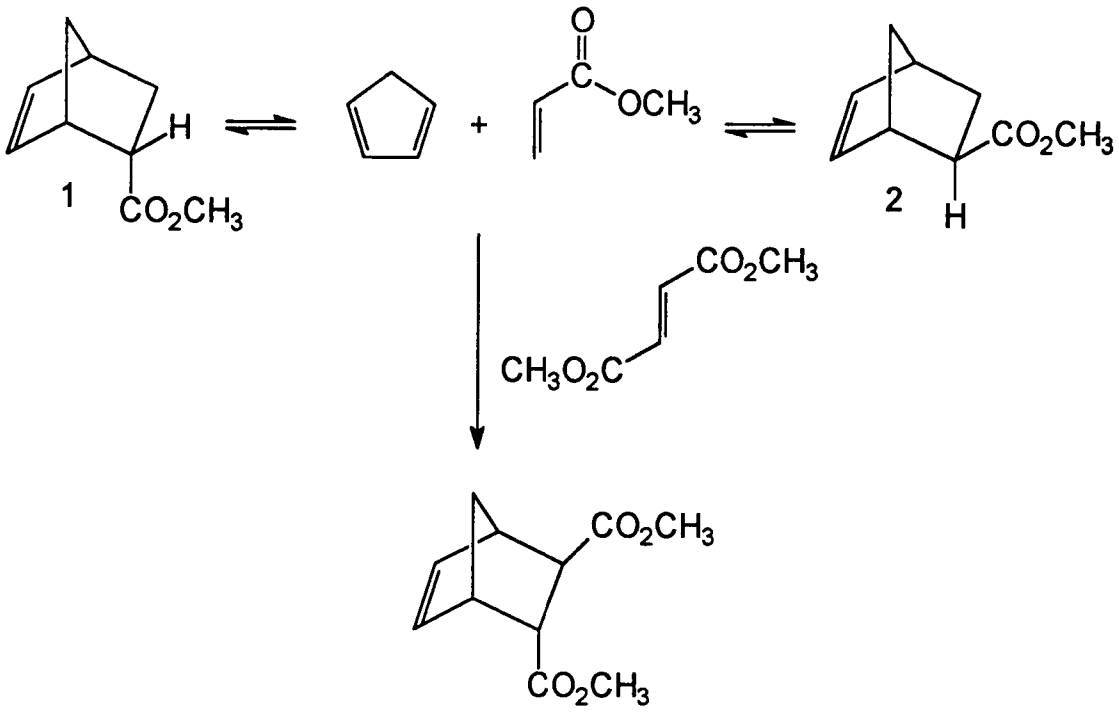
In the alternative mechanism, the *endo* and *exo* adducts would undergo a retro-Diels Alder reaction to regenerate cyclopentadiene and methyl acrylate which would then react preferentially to form the endo adduct. If this pathway were

Scheme 2



correct, it should be possible to trap cyclopentadiene with a more reactive dienophile. Indeed, when the *endo* adduct was treated with highly reactive dimethyl fumarate on Al_2O_3, the cyclopentadiene-dimethyl fumarate adduct was obtained as described in Scheme 3. When alumina was treated with a solution of dimethyl fumarate (DMF) in ethyl ether, the dimethyl fumarate was strongly absorbed to the solid and remained on the solid when the solvent was removed under vacuo and the solid dried (DMF/Al_2O_2). The trapping reaction was attempted

Scheme 3



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at different temperatures with various weight ratios of DMF:(Al_2O_3+esters) (Table 10). The products of the reaction were isolated and analyzed by GC/MS, ^{13}C, and ^1H NMR spectroscopies for dimethyl-*trans*-norbor-2-ene-5,6-dicarboxylate (**7**). The synthesis of **7** was verified by comparison of the spectoscopic data, with those of an independently synthesized material. The data (Table 10) indicate that the maximum yield of **7** was obtained, with a weight ratio DMF:(Al_2O_3+ester) = 0.05. In conclusion, the data (Table 10) support the interpretation that cyclopentadiene generated *in situ* in the retro-Diels-Alder reaction undergoes the 4+2 cycloaddition reaction with DMF.

Table 10

Trapping of CP by DMF in the Reaction of *Endo*-Ester (1) With 400°-Al_2O_3 at 60°C

Reaction Time	Reactants	1(%)	5(%)
10 hours	22 mmol Endo + 55 mmol DMF/10 g Al_2O_3	100	0
10 hours	1.5 mmol Endo + 11 mmol DMF/12 g Al_2O_3	98	2
20 hours	7.8 mmol Endo + 2.2 mmol DMF/12 g Al_2O_3	80	20

[a]Determined by H-1 NMR.

3.4 *H-D Exchange of Addends on the Surface of D-Al_2O_3*

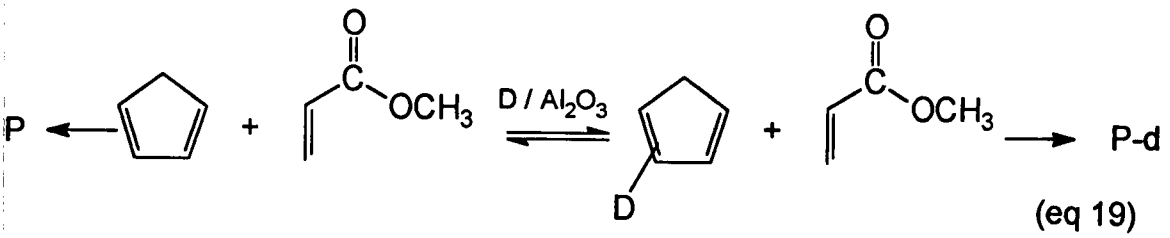
As described earlier, alumina is basic enough to allow hydrogen exchange between itself and an acidic substrate. Thus, when cyclopentadiene was treated with 400°-D/Al_2O_3, which was 96% deuterated, analysis by GC/MS indicated that the cyclopentadiene-dimer was 43% deuterated (Table 11). In addition, when cyclopentadiene was treated with methyl acrylate on 400°-D/Al_2O_3, both the cyclopentadiene-dimer (24% d) and the *endo* adduct (27% d) were extensively deuterated (eq 19). This contrasts with the reaction of cyclopentadiene with dimethyl fumarate on the same alumina, where recovered cyclopentadiene dimer was 32% deuterated while the cyclopentadiene-dimethyl fumarate adduct

Table 11

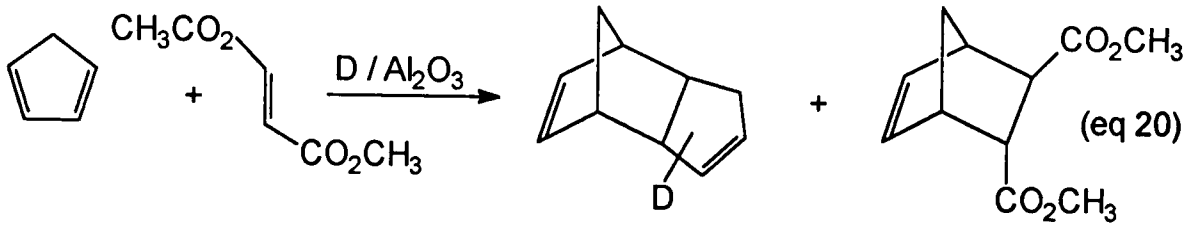
Deuterium Incorporation
in the Generated CP-CP, CP-MA, CP-DMF Adducts
on 400°-D/Al_2O_3

Reagents (mmol)	Reaction Conditions			Deuterium Incorporation Adducts		
	$A1_2O_3$(g)	t(h)	T(°C)	CP-Dimer	N	CP-DMF
CP(16)	10	1	60	15% d_0 29% d_1 27% d_2 19% d_3 6.5% d_4 1.8% d_5 1.7% d_6		
CP(8.3) + MA(7.5)	12	1	70	53% d_0 16% d_1 16% d_2 10% d_3 3.4% d_4 1.4% d_5 0.6% d_6	49% d_0 35% d_1 12% d_2 3.5% d_3 0.3% d_4	
CP(8.3) + DMF(7.5)	16	1	60	6.6% d_0 5.6% d_1 9.2% d_2 18.6% d_3 22% d_4 22% d_5 16% d_6		100% d_0

contained no deuterium (eq 20)



(eq 19)



(eq 20)

32 % -d 0 % -d

The incorporation of deuterium in the cycloadducts can be easily rationalized via a rapid proton exchange between cyclopentadiene and deuterated alumina being competitive with the formation of the adducts. This hypothesis is supported by the mass spectrum of recovered deuterated *endo* carbomethoxy ester in which all deuterium was detected at positions originally associated with the cyclopentadiene. Thus the deuterium content, determined at the fragment 66 m/e obtained from the molecular ion (152 m/e) via a retro-Diels-Alder reaction, was nearly identical (27%) to that of the molecular ion itself (28%). This is expected if the *endo* ester contains no deuterium at the carbon α to the carbonyl group.

The decrease in the deuterium content from cyclopentadiene dimer (32%), to *endo* adduct (27%), to CP+DMF adduct (0%) parallels the increase in the rate of their formation from the addends observed in solution (51). In the reaction of cyclopentadiene with dimethyl fumarate, the DMF-CP adduct forms much more rapidly than deuterium exchange on cyclopentadiene. The considerable

deuteration of the *endo* adduct, however, contrasts significantly with the results of the epimerization of *endo* and *exo* adducts on 400°-D/Al_2O_3 where neither recovered *endo* nor *exo* adducts contained deuterium.

When the trapping experiment of cyclopentadiene formed in the retro-Diels-Alder reaction of the esters with DMF was run on D/Al_2O_3, none of the adducts contained deuterium. The distinct difference in behavior of cyclopentadiene and methyl acrylate when generated in the retro-Diels-Alder reaction and independently subjected to 400°-D/Al_2O_3 implies that, in the former cases, the addends never escape each other's presence before they react to reform the exo and endo adducts. If they did, cyclopentadiene would have incorporated deuterium. Berson (49) has also observed a similar effect. He reported, that when the *endo*-cyclopentadiene-maleic anhydride adduct which was radioactively labeled in the carbonyl carbons (^{14}C), was refluxed in decalin with an equimolar quantity of inactive maleic anhydride, the *exo* isomer that formed had an activity higher than that theoretically possible (50% of *endo*) if it were formed entirely by a dissociation-recombination mechanism. Up to 45% of *exo* adduct arose by a pathway which did not involve dissociation into kinetically free addends. It was suggested that the cyclopentadiene-maleic anhydride adduct formed a complex held together by electronic interactions; the components could then rotate with respect to each other, resulting ultimately in either the *endo* or *exo* adduct. Similarly in the present case, if it is assumed that cyclopentadiene and maleic anhydride are never kinetically distinct species when formed in the retro-Diels-

Alder pathway, the reaction of the cylcopentadiene generated *in situ* with DMF must occur by a pre-association mechanism. Only when dimethyl fumarate is in the vicinity of the cyclopentadiene-methyl acrylate complex will trapping occur. Pre-association mechanisms are reasonable in that they have been detected in carbonyl additions, nucleophilic aromatic substitutions, electrophilic aromatic substitutions, and free radical chlorinations (50-53).

CHAPTER IV

Diels-Alder Reaction of Cyclopentadiene With Methyl Acrylate on Zeolites

Rate acceleration and enhancement in stereo- and regioselectivity of Diels-Alder reactions in zeolites are of current interest (54,55). The catalytic activity of zeolites is attributed to the acid and basic sites present in their interior and also to their well-defined intracrystalline porestructure. It was thus of interest to run the cycloaddition of methyl acrylate with cyclopentadiene on zeolite 5Å and compare the results to those obtained with alumina. A series of reactions were run on unactivated zeolite 5Å and zeolite 5Å activated at 400 °C at two loadings of methyl acrylate and cyclopentadiene. The reactions were run at 50 °C for 5 h. The results are summarized in Table 12.

Table 12

The Effect of Surface Loading on the *Endo* to *Exo* Ratio Using Zeolite 5A°

Activation Temperature	5:1[a]	Yield(%)[b]	10:1[a]	Yield(%)[b]
Unactivated	3.4[c]	78	3.7[c]	71
400°	3.4	75	4.2	70

[a] Zeolite:(MA+CP) (w:w) used.
[b] Isolated. [c] *Endo:Exo* ratio.

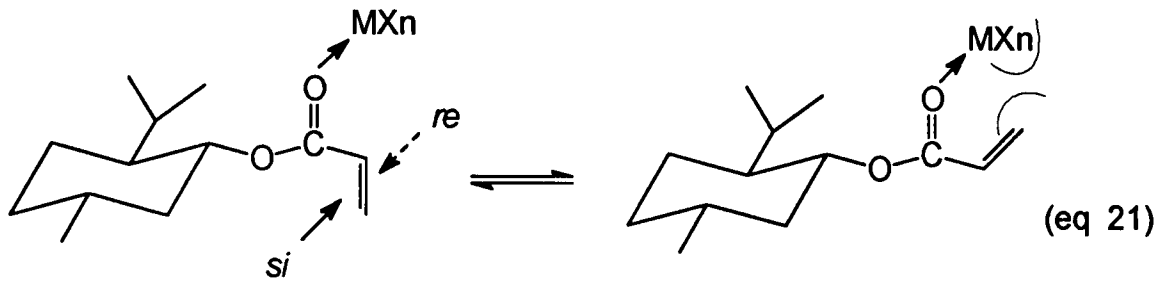
The results show that unlike alumina, the diastereoselectivity of the reaction of cyclopentadiene with methyl acrylate on zeolite 5Å is low; the reaction behaves as if there were no solid present. It should be mentioned, however, that it has recently been reported that the Diels-Alder reaction of cyclopentadiene with methyl acrylate in the presence of Na-Y zeolite afforded an *exo:endo* ratio of 24. This reaction was run in the presence of CH_2Cl_2 as a solvent at 0 °C (53-55).

CHAPTER V

Alumina-Catalysed Asymmetric Diels-Alder Reaction of Cyclopentadiene With (-)-Menthyl Acrylate.

The most attractive feature of the Diels-Alder reaction is the simultaneous, regioselective formation of two bonds leading to the creation of up to four chiral centers at the binding sites with predictable relative stereochemistry. If either the diene or the dienophile is chiral and optically active, facially selective addition gives rise to a non-statistical mixture of optically active diastereomers (56).

In the Diels-Alder reaction of cyclopentadiene with (-)-menthyl acrylate, the attachment of the chiral (-)menthyl group to the dienophile causes steric shielding of the *re*-face thereby directing the addition of the diene to the *si*-face (eq 21).



(eq 21)

7a 7b

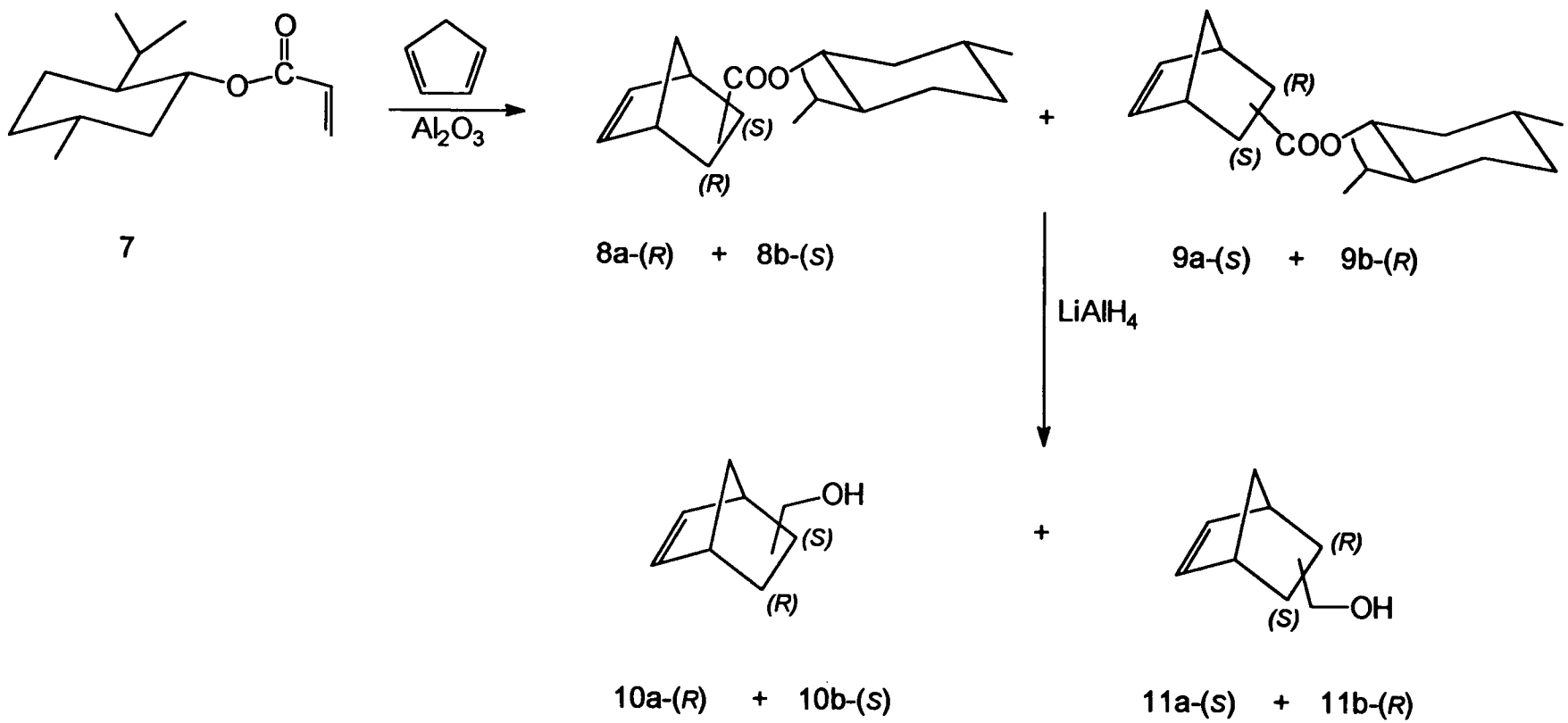
MXn = Lewis acid

As a result of the advantageous coincidence of the effects of the π-face differentiation and the *endo* selectivity, one diastereomer usually predominates

In general, thermal reactions give only low optical yields and the best results have been obtained in reactions catalyzed by Lewis acids at low temperatures (60-65). In the catalyzed reactions, the dienophile adopts the *transoid* conformation **7a**, in which the catalyst is coordinated with the carbonyl oxygen *anti* to the ether oxygen, rather than the more sterically hindered *cisoid* conformation **7b** (eq 21). If the diene adds exclusively to the π-face opposite the isopropyl group in the menthyl moiety (larger group), conformers **7a** and **7b** display reversed topicity. Consistent with this analysisis is the fact that no Diels-Alder reactions of acrylates have ever surpassed 65% diastereomeric excess.

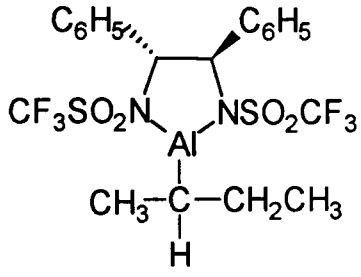
The reaction of cyclopentadiene with optically active (-)-menthyl acrylate was first studied in solution by Sauer (57) and later by Farmer (58). When the reaction was run neat at 25 °C for 6 h, it afforded a 69:31 mixture of *endo*(**9a**+**9b**):*exo*(**10a**+**10b**) adducts; separation of the *endo* adducts by column chromatography, followed by reduction with $LiAlH_4$, resulted in an a 8% optical purity for the *(+)-R-endo*-alcohol (**11b**) (Scheme 4). Both the *endo-exo* selectivity and the optical yield were much improved when the reaction was repeated at a lower temperature in the presence of a catalyst (58,59). Then an *endo:exo* ratio of 89:11 was obtained at 4-8 °C with $SnCl_4$ (1:1 equiv); however, the reaction afforded an optical yield of 41% for **11b**. Other Lewis acids tested were moderately more successful in inducing higher optical yields for **11b** and better *endo* selectivities, particularly at lower temperatures (58,59). Thus, $AlCl_3$ (0.7 equiv per 1.0 equiv of acrylate) at -55 °C afforded a 48% optical yield,

Scheme 4


O
O
C
Al_2O_3
COO
(S)
(R)
+
(R)
(S)
COO
7
8a-(R) + 8b-(S)
9a-(S) + 9b-(R)
$LiAlH_4$
OH
(S)
(R)
+
(R)
(S)
OH
10a-(R) + 10b-(S)
11a-(S) + 11b-(R)

and $TiCl_4$ (1.5 eq per 1.0 eq of acrylate) at -20 °C gave an *endo:exo* ratio of 92:8 and an optical yield of 62%.

Recently, attempts were made to increase both the diastereoselectivity and the *endo-exo* selectivity in Diels-Alder reactions using optically active Lewis acid catalysts. Thus, the reaction of cyclopentadiene and methyl acrylate in the presence of (-)-menthoxyaluminum dichloride at -78 °C afforded a 6% optical purity for the *S-(-)-endo*-ester **1a** (61). Recently, Corey (61) reported that in the presence of the cyclic amidoaluminum isobutyl catalyst shown below the reaction of cyclopentadiene with (-)-menthyl acrylate at -78 °C afforded an *endo:exo* ratio of 85:15; the reaction provided **11b** in 97% optical yield.



Since activated alumina is a Lewis acid catalyst, it was of interest to study the Diels-Alder reaction of cyclopentadiene with (-)-menthyl acrylate in the presence of this solid.

5.1 *Results and Discussion*

The reaction of cyclopentadiene with (-)-menthyl acrylate was studied using out-of-the-bottle alumina and aluminas activated at 400° C, 600° C, and 800° C, respectively. The reactions (Table 13) were run at temperatures ranging from -

78° C to +65° C for various amounts of time, and employed a weight to weight ratio of alumina to reagents of 15:1. In all runs, 7.55 mmoles each of (-)-menthyl acrylate and cyclopentadiene was used. The *endo* to *exo* ratio of the adducts was established by GC/MS analysis and the degree of asymmetric induction was assessed entirely by chiroptic measurements. In the gas chromatogram of the esters, the *exo* diastereomeric adducts eluted first as a single peak with retention time of 15.7 min followed by the *endo* adducts which were marginally resolved into two peaks of retention times 15.9, and 16.1 min. The peak at 15.9 min was assigned to the *(S,S)* adduct (**9a**) whereas that at 16.1 min was assigned to its *(R,R)* isomer (**9b**). These assignments were made by comparison of the GC data obtained in the alumina catalyzed reactions with those obtained by Cativiela in the reaction of cyclopentadiene and (-)-menthyl acrylate using Zn(II)-exchanged K10 montmorillonite as catalyst (62). The mass spectra of the *exo* and *endo* adducts were identical. They revealed a molecular ion of low intensity at 276 m/e, a base peak at 66 m/e, and a moderate intensity peak at 139 m/e due to the menthyl ion. In order to determine the diastereomeric excess of the **9**-*endo* adducts, the mixture of the (-)-menthyl esters was reduced to the corresponding alcohols by $LiAlH_4$ in ether. The *endo*-norbornyl alcohols, **11a** + **11b**, were isolated by preparative GC on a 30% carbowax column, analyzed by ^{13}C and ^{1}H NMR, and the optical purity of the mixture measured in 95% ethanol. The rotations and configurations of the alcohols **11a** and **11b** have been assigned by

Berson (49). The alcohol **11b**, for example, has the *(R)*-configuration at C-3 and in 95% ethanol $[\alpha]_D^{25} = +76.6°$.

The Diels-Alder reaction of cyclopentadiene and (-)-menthyl acrylate was first run neat. Analysis of the esters by GC indicated an *endo:exo* ratio of 2.4, and treatment as previously described, revealed a diastereomeric excess of 9% for **11b**. This value is in excellent agreement with previously published results (58). On unactivated alumina the *endo:exo* ratio rose to 4.3 and the diastereomeric excess improved to 14.9%. In this case the change in the *endo:exo* ratio conforms to the polarity of the medium effect found by Berson for the reaction of achiral acrylates with cyclopentadiene (23). The modest π-face differentiation observed could also be related to polarity effects. It is possible that alumina stabilizes one of the π-faces of the acrylate during the addition of the cyclopentadiene, thus lowering the energy of activation of the cycloaddition.

When the reaction was run at 25 °C on alumina activated at 400 °C for 4 h, an *endo:exo* ratio of 8.5 was obtained; the diastereomeric excess of the reaction was 29% in favour of **11b** . The increase in the *endo:exo* ratio observed can be attributed to the defect sites created upon activation of the solid, which influence the *endo:exo* ratio in a manner similar to that observed in the reaction of cyclopentadiene with methyl acrylate, but to a lesser extent. Perhaps this could be due to unfavorable steric factors encountered in the interaction of the menthyl moiety of the acrylate with the surface of alumina. As can be seen in Table 13, additional improvement in the two selectivities was attained by running the

reaction on the 400°-Al_2O_3 at increasingly lower temperatures, with an *endo:exo* ratio of 15.2 being observed at -78° C and a diastereomeric excess of 36% for **9b**. This value was obtained by GC analysis of the *endo* esters **9a** and **9b**.

Table 13

Endo:Exo Ratio in the Reaction of
(-)-Menthyl Acrylate and Cyclopentadiene

Reaction Temp. (°C)	Alumina Type[a]				
	Neat	Unact	400°	600°	800°
-65	2.4	4.3	8.1	1.2	1.2
-25			8.5	3.2	1.6
-0			9.0		3.2
-10				4.9	
-78			15.2		

[a] The activated alumina was heated for 4 h at the indicated temp.

The plot of ln$N$/ln$K$ against the reciprocal of absolute temperature (1/T in K) on 400°-Al_2O_3 activated for 4 h gave a straight line for reaction temperatures ranging from -78° C to +65° C. The linearity of this plot also suggests the operation of a single mechanism on the 400° -Al_2O_3 influenced by the same type of active sites. From the slope and intercept of this plot, $[\ln(N/X) = (305 \pm 29)T^{-1}$

+ (114±0.11) (correlation coefficient = 0.9860)] $\Delta H^{\ddagger}N$- $\Delta H^{\ddagger}_X$ = -(606 ± 57) cal mol^{-1} and $\Delta S^{\ddagger}_N$-$\Delta S^{\ddagger}_X$ = -(2.27 ± 0.22) cal K^{-1} mol^{-1} were obtained.

When the reaction was repeated on alumina which had been activated at 600 °C and 800 °C for 4 h, both the *endo-exo* selectivity and the diastereoselectivity were reduced (Table 14). Thus for a reaction run at 65 °C on both aluminas, a mixture of *endo:exo* adducts of 1.2 was obtained. This represents a decrease in the *endo* selectivity relative to the 400°Al_2O_3 by a factor of 85%. Similarly, on the reaction run on 0 °C on 800°-Al_2O_3 the *endo:exo* selectivity decreased by a factor of 64% and the diastereomeric excess by a factor of 22%. As expected, a decrease in temperature increases both selectivities obtained but the overall yield was diminished.

These findings are reminiscent of the effect of 800°-Al_2O_3 on the cycloaddition of cyclopentadiene and the methyl acrylate and is due to the facile reversibility of the Diels-Alder reaction on the 800°-solid. The diminished *endo:exo* selectivity observed on 600°-Al_2O_3 can be explained in a similar manner. As it was discussed earlier, when alumina is heated above 400 °C, a new kind of site is exposed to the surface which is considerably more active as a catalyst for the retro-Diels-Alder reaction which ultimately has the effect of reducing the *endo:exo* and diastereophase selectivities.

Table 14

Diastereomeric Excess in the Reaction of
(-)-Menthyl Acrylate and Cyclopentadiene

Reaction Temp. (°C)	Alumina Type			
	Neat	Unact	400°	800°
-65	9.0	14.9		
-25			29.0	
-0			29.1	22.6
-10			33.7	26.0
-78			36.0	

[a]Activated for 4 h at the indicated temp.

Even larger diastereomeric excesses were achieved by running the reactions on alumina activated at 400 °C for times greater than 4 h. As shown in Table 15, the diastereomeric excess of **11b** increases at all reaction temperatures as the activation time increases. Furthermore, the data show that the diastereomeric excess can be moderately improved on all aluminas by lowering the reaction temperature. Thus, a diastereomeric excess of 35.6% was obtained at -10 °C on alumina activated at 400 °C for 24 hours. This represents a 14% increase in diastereomeric excess from that obtained at 65 °C on alumina activated for 6 h.

Table 15

Percent Diastereomeric Excess on 400°-Al_2O_3 as a Function of Activation Time.

Reaction Temp. (°C)	% Diastereomeric Excess			
	4 h[a]	6h[a]	12h[a]	24h[a]
65		25.6		
25	29.0	28.2	31.6	32.3
0	29.1	31.5	31.7	32.9
-10	33.7		32.7	35.6

[a] Activation time

When ln **(11b)/(11a)**, derived from the percent diastereomeric excess, was plotted against reciprocal of the temperature, [1/T(in K)] for the reaction run at various temperatures on alumina activated for 6 h, a straight line was obtained. This indicates that, on 400°-Al_2O_3, the reaction of cyclopentadiene with (-)-menthyl acrylate takes place by a single mechanism, and a single reaction intermediate should be involved in the reaction. Extrapolation of the data to -78 °C afforded a diastereomeric excess for **11b** of 42%. From the equation, ln **(11b/11a)** $=(167 \pm 33)\ T^{-1} + (0.031 \pm 0.016)$ (correlation coefficient = 0.9631), the difference in activation energy and activation entropy of the reaction leading to **11b** and **11a** [$\Delta H^{\ddagger}$ **(11b)**-$\Delta H^{\ddagger}$ **(11a)** and $\Delta S^{\ddagger}$ **(11b)**-$\Delta S^{\ddagger}$ **(11a)**] are estimated to be (-332 ± 66) cal mol^{-1} and (0.062 ± 0.032) cal $mol^{-1}\ K^{-1}$, respectively.

In an attempt to perform asymmetric induction in a different manner, the achiral surface of alumina, was rendered chiral by absorption of (-)-menthol, a

suitable optically active addend. The Diels-Alder reaction of optically inactive substrates on alumina treated in such a manner should then generate adducts which were optically active. Based on the previous findings, the loading of reagents onto the surface can profoundly influence the selectivity of the reaction. Having too many molecules on the surface reduces the selectivity. For this study to be successful, it was necessary to determine the proper amount of menthol that renders the surface as chiral as possible but at the same time, doesn't cover all active sites on the solid. The cycloaddition reaction of methyl acrylate and cyclopentadiene was run for 4 h at 65 °C on 400 °C activated Al_2O_3 coated with various amounts of a (-)-menthol. The weight to weight ratio of Al_2O_3 to the reagents was 10:1, whereas the weight to weight ratio of (-)-menthol to alumina varied from 2:1 to 0.002:1. The method of loading the (-)-menthol on alumina was straightforward. The appropriate amount of (-)-menthol, dissolved in ethyl ether was taken up at 25 °C by 11.5 g of alumina activated for 4 h at 400 °C. After cautious evaporation of the solvent under reduced pressure at 25 °C, the solid was chilled to 0 °C and loaded with a 7.55 mmoles of methyl acrylate and 7.47 mmoles cyclopentadiene. The reaction flask was immersed in a preheated oil bath at 65 °C and the reaction run for 4 h with continuous stirring. Successive extractions of the solid with ether gave a mixture, which by GC/MS analysis, revealed the *endo-exo* selectivity of the ester adducts (Table 16). Removal of (-)-menthol and cyclopentadiene dimer by column chromatography (hexanes/EtOAc 19:1) afforded pure ester adducts.

Table 16

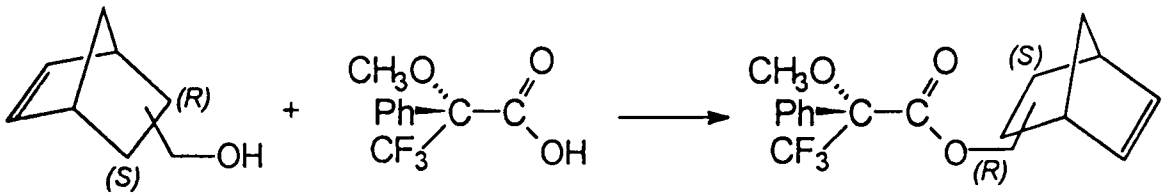
Endo:Exo Selectivity of CP + MA[a] on 400°-Al_2O_3 Coated With (-)-Menthol

	Menthol:Al_2O_3 w/w	Al_2O_3:(CP+MA) w/w	*Endo: Exo*
1	2/1	10/1	4.2
2	1/1	10/1	4.0
3	.5/1	10/1	2.8
4	.2/1	10/1	3.4
5	.05/1	10/1	4.5
6	.01/1	10/1	4.3
7	.005/1	10/1	6.3
8	.002/1	10/1	45.0

a) at 65 °C

Reduction of the ester adducts with $LiAlH_4$ furnished the corresponding alcohols **11** and **12.** Removal of the *exo*-isomers (**12**) by preparative GC on a 30% Carbowax on Chromosorb w 80/100 mesh column at 190 °C afforded **11** as a mixture of enantiomers. The enantiomeric purity of **11** was determined by measuring its optical rotation in 95% ethanol and by ^{19}F NMR analysis as follows. The enantiomeric mixture of alcohol (**11**) was esterified with (+)-α-methoxy-α-trifluoromethylphenyl acetic acid in the presence of dicyclohexylcarbodiimide and dimethylaminopyridine in CH_2Cl_2 for 2 h. Filtration and column chromatography (hexanes/EtOAc 19:1) furnished an inseparable mixture of the diastereomeric

esters **13** and **14**. The diastereomeric purity of this mixture was determined by ^{19}F NMR-analysis in the presence of $Eu(fod)_3$ (eq 23).



11a + 11b (*R*)-(+)-MTPA 13-(*S*) + 14-(*R*)

(eq 23)

According to findings by Oppolzer (56), the (+)-MTPA ester (**13**) of the *endo*-(+)-*R*-alcohol (**11b**) shows a ^{19}F singlet 0.15 ppm upfield from that of the corresponding ester **14** derived from *endo*-(-)-(*S*)-alcohol (**11a**). All alcohols examined showed no optical rotation except the one obtained from the reaction on alumina coated with (-)-menthol (menthol:Al_2O_3 w,w ratio of .01:1). This mixture of *endo* alcohols showed a small optical reaction of $[a]^{25}_D$ = 0.008° which indicated a 2% enantiomeric excess for **11b**. This value however was too small to be independently confirmed by ^{19}F NMR. When this mixture of enantiomeric alcohols was converted to their (+)-MTPA ester derivatives and subjected to ^{19}F NMR analysis in the presence of $Eu(fod)_3$, it gave two singlets which upon integration showed a 1:1 ratio of diastereomers.

The difference in chemical shift (Δ, ppm) of the fluorine signals of the trifluoromethyl groups in the (-)-*S* (lowfield)(**14**) and (+)-*R* (upfield) (**13**) MTPA esters, as a function of the molar ratio of $Eu(fod)_3$: (+) MTPA-esters at 27° C, is shown in Table 17. In the ^1H NMR spectrum, the methoxy signals due to

diastereomeric MTPA-esters were not resolved and gave a singlet at 3.50 ppm. These signals however were resolved upon addition of $Eu(fod)_3$. For example with a molar ratio $Eu(fod)_3$:MTPA of 0.31, the methoxy signals were resolved and had shifted downfield to 5.75 and 5.63 ppm, respectively. Integration of these signals also indicated a 1:1 ratio of diastereomers

When the reaction was repeated on cellulose, a naturally occuring, optically active solid, a 78:28 ratio of *endo:exo* esters in 68% yield was obtained; the *endo* adduct was optically inactive.

In an attempt to increase the stereoselectivity of the reaction of cyclopentadiene with (-)-menthyl acrylate, the surface of alumina was coated with variable amounts of L-(+)-glutamic acid and, in one case with (-)-menthol, and the reaction was run on the solids for 4 hours at 60 °C. The weight to weight ratio of alumina to menthyl acrylate and cyclopentadiene was 15:1. The glutamic acid was coated on alumina in a manner similar to that described earlier for menthol. The results obtained are summarized on Table 18. The data in Table 18 (entries 2-4 vs Table 15 entry 1) show, that chiral agents coated on alumina in small amounts do not influence the diastereomeric excess of this reaction. As it shown earlier, the *endo:exo* ratio and the diastereomeric excesses appear to be influenced more by the activation temperature of the alumina rather than the loading or type of chiral R^* agent coated on the solid.

Table 17

The Effect of the Molar Ratio of Eu(fod):±MTPA Esters (**13** + **14**) in the Chemical Shift Difference of the ^{19}F NMR Signals of the Trifluoromethyl Groups of the esters

$Eu(fod)_3$:MTPA mol/mol	Δ (ppm)
0.00	0.05
0.28	0.16
0.31	0.17
0.47	0.18
0.56	0.19
0.70	0.21
0.86	0.21

Table 18

Effect of Al_2O_3 Coated With Chiral Agents
in the *Endo:Exo* and Diastereophase Selectivities
in the Reaction of (-)-Menthyl Acrylate
and Cyclopentadiene

Entry	R*	R*:Al_2O_3[a]	*Endo%*	%de[b]	Alumina Type
1	Glutamic Acid	.5/1	90		400°
2	Glutamic Acid	.05/1	90	25	400°
3	Glutamic Acid	.1/1	81	16	200°
4	Menthol	.1/1	--	24	400°

[a]Weight to weight ratio of agent to alumina.
[b]Diastereomeric excess.

Conclusion

The Diels-Alder reaction of methyl acrylate with cyclopentadiene on activated alumina affords large *endo* to *exo* selectivities in high yields. The *endo* to *exo* selectivity was shown to be dependant on the loading of the addends on the surface, the lower the loading the higher the selectivity, and the temperature of activation. For alumina activated up to 300 °C the selectivity was moderate (10:1) and corresponded to the number of aluminum ions exposed on the surface. Activation at 400 °C results in a sharp increase in the *endo* to *exo* ratio (52:1), which is attributed to the creation of distinct sites on the surface of considerable catalytic activity. At higher temperatures of activation the selectivity diminishes significantly to nearly equilibrium values (1:1). This is the result of yet another catalytic site formed on the surface of alumina of considerably different properties and characteristics. Our results corroborate existing theories on the surface characteristics of alumina.

Alumina was also shown to be a promising catalyst in assymetric synthesis. The reaction of cyclopentadiene with (-)-menthyl acrylate at low temperature (-78 °C) on activated alunina (400°/6h) afforded a 42% diastereoface selectivity for the endo ester with the *s*-configuration at the α carbon to the carbonyl group.

Experimental Section

Nuclear magnetic resonance spectra were recorded on Jeol FX 90Q and Bruker AC-250 spectrometers in $CDCl_3$ with tetramethylsilane as the internal standard. Preparative gas chromatography (GC) was performed on a Varian Aerograph Series 1700 instrument, using a 3/8 -in. × 10-ft 30% Carbowax 20M on 60-80 mesh Chromosorb W column maintained at 180 °C with a He flow of 150 cc/min. Analytical GC was performed on a Varian Model 3700 instrument using a 1/4 -in. × 12-ft 15% SE-30 on Chromosorb W column at the oven; the temperatures were programed starting at 70 °C (1 min) with rise rate of 20 °C/min and then maintained at 200 °C (30 min) with a He flow of 40 cc/min. GC/MS was carried out on a Hewlett-Packard HP 98785 A instrument, using a 0.2 mm × 25 mm cross-linked methyl silicone column at an initial oven temperature of 80 °C (1 min); The rise rate was 25 °C/min up to 150 °C (10 min) with a He flow 10 p.s.i. Optical rotations were obtained on a Perkin Elmer Model 341 instument. Brockmann activity grade 1 neutral alumina (Fisher Scientific Co.) was employed in all reactions. All experiments were carried out under an atmosphere of dry argon. The products were purified by column chromatography on silica 60 Å. Cyclopentadiene was obtained by pyrolysis of dicyclopentadiene and stored over 4 Å molecular sieves in the freezer. The low temperature reactions (3 °C, 0 °C and -10 °C) were run using a Brickmann Model RM 6 constant temperature instrument.

Reaction of Cyclopentadiene with Methyl Acrylate on Unactivated Alumina. To an argon flushed, 50-mL round-bottomed flask fitted with a condenser and a stirring bar and cooled to 0 °C, were added, out-of the bottle alumina (11.4 g), and methyl acrylate (7.50 mmol, 0.645 g). The solid was stirred for 15 min and then freshly distilled cyclopentadiene (7.50 mmol, 0.495 g) was added. The reaction was maintained at 50 °C (oil bath) for 5 h with stirring. After cooling, the unreacted starting materials and products were removed from the solid by extraction with anhydrous ether (5 × 20 mL). The *endo/exo* ratio of the cycloadducts **1** and **2** was determined: by GC/MS analysis [t_R (*endo*-adduct **1**)= 7.63 min, t_R (*exo*-adduct **2**)= 7.47 min]. The column temperature was programed from 80 °C (1 min) at 25 °C/min up to a maximum 150 °C (10 min). GC analysis was also carried out [t_R (*endo*-adduct **1**)= 12.3 min, t_R (*exo*-adduct **2**)= 12.1 min] on a 15% SE-30 on Chromosorb W column using an initial oven temperature of 70 °C (1 min) and then rise rate of 20 °C/min to 200 °C (30 min). ^{1}H NMR ($CDCl_3$) analysis indicated δ (**1**-OCH_3) 3.61, (**2**-OCH_3) 3.68. Evaporation of the solvent and purification by column chromatography (ether/hexane = 1 : 30 as eluant) gave the Diels-Alder adducts **1** and **2** in 62% yield. This procedure was then repeated with different weights of alumina, 5.70 g, 4.60 g, 0.451 g, 0.110 g, 0.057 g, and 0.034 g, with 57%, 60%, 55%, 53%, 57%, and 54% **1** and **2** being generated, respectively.

Preparation of Activated Alumina. The dehydration of alumina was carried out by placing alumina (200 g) in a 500-mL round-bottomed flask which was

connected to a vacuum system through a cold trap maintained at -78 °C. The entire system was evacuated to 0.005 mm Hg. The round-bottomed flask containing the alumina was then heated to the appropriate temperature and the water vapor collected in the cold trap. The round-bottomed flask was periodically sealed from the vacuum and removed from the system under vacuum, and shaken. At the end of the desired time of activation the alumina was allowed to cool under vacuum and stored under argon. Further handling of the alumina was carried out in a glove bag under an atmosphere of argon.

Reaction of Cyclopentadiene with Methyl Acrylate on Activated Alumina. To three 50-mL round-bottomed flasks, each containing alumina (5.80 g) which had been activated for 4 h at 200 °C, 300 °C, and 400 °C, respectively, were added, at 0 °C under argon, methyl acrylate (7.50 mmol, 0.645 g) and freshly distilled cyclopentadiene (7.50 mmol, 0.495 g). The reaction was maintained at 55 °C (oil bath) for 5 h with stirring. After cooling, the unreacted starting materials and products were removed from the solid by extraction with anhydrous ether (5 × 20 mL). The *endo/exo* ratio of the cycloadducts **1** and **2** was determined by GC analysis [t_R (*endo*-adduct **1**)= 12.5 min, t_R (*exo*-adduct **2**)= 12.2 min] on a 15% SE-30 on Chromosorb W column, and by ^{1}H NMR. Workup and analysis as previously described yielded the following results (alumina, *endo/exo* ratio, percent yield of **1** and **2**: 200°, 5.0, 56%; 300°, 6.8, 60%; 400°, 40, 63%.

The procedure was then repeated using 11.4 g of the above aluminas, methyl acrylate (7.50 mmol, 0.645 g) and cyclopentadiene (7.50 mmol, 0.495 g). Workup

and analysis as previously described, yielded the following results (alumina, *endo/exo* ratio, percent yield of **1** and **2**): 200°, 5.8, 63%; 300°, 7.0, 60%; 400°, 52, 67%.

The Reaction of Cyclopentadiene with Methyl Acrylate on Activated Alumina as a Function of Time. To a 50-mL round-bottomed flask containing alumina (11.4 g) that had been activated at 400 °C for 4 h, were added methyl acrylate (7.50 mmol, 0.645 g) and freshly distilled cyclopentadiene (7.50 mmol, 0.495 g). Four batches were prepared and each batch was allowed to react at 55 °C, one for 0.5 h, one for 1.0 h, another for 2.0 h, and the fourth for 5 h. The reaction was maintained at 55 °C (oil bath) for 5 h with stirring. After cooling, the unreacted starting materials and products were removed from the solid by extraction with anhydrous ether (5 × 20 mL). Workup and analysis as previously described, yielded the following results (hours, *endo/exo* ratio, percent yield of **1** and **2**): 0.5 h, 55, 53%; 1.0 h, 57, 56%; 2.0 h, 48, 55%; and 5.0 h, 52, 62%.

Preparation of Deuterated Alumina. The deuteration of alumina was carried out by placing alumina (50.0 g) in a 250-mL round-bottomed flask, equipped with a side arm which was connected to a vacuum system through a cold trap maintained at -78°. The entire system was evacuated to 0.005 mm Hg. The flask was then heated to 400° and the water vapor was collected in the trap. After 6 h the heating mantle was removed, and the dehydrated alumina allowed to cool. The flask was closed off from the vacuum and D_2O (3 mL) was injected on to the alumina through a septum. The evacuated flask was then heated to 350° for 6 h.

The alumina was then slightly cooled and the flask was reopened to the vacuum and heated for an additional 6 to 8 h. The process was repeated 5 times.

Determination of Percent Deuteration of Alumina. To a 5-mL flask containing a mixture of D_2O and H_2O (0.844 g) collected during dehydration of alumina, was added, $(CH_3)_4N^+Br^-$ (II) (5.48 mmol, 0.844 g) and the relative areas of the hydrogen in water to hydrogen in (II) were determined by ^1H NMR using the following equations:

$$\frac{\text{area}_{\text{water}}}{\text{area}_{\text{II}}} = \frac{2\ \text{mole}_{\text{H2O}}}{12\ \text{mole}_{\text{II}}} \quad \text{and}$$

$$\text{mole}_{\text{H2O}} \times M_{\text{rH2O}} + \text{mole}_{\text{D2O}} \times M_{\text{rD2O}} = \text{weight of } H_2O$$

It was determined that the alumina was 96% deuterated. The proton signal in H_2O resonated at δ 4.60 ppm that of (II) at δ 3.20 ppm.

Epimerization of methyl 5-*exo*-2-norbornene Carboxylate (2) to its *endo*-isomer (1) on Deuterated Activated Alumina. In a 50-mL round-bottomed flask was placed, at 0 °C, 400°- D/Al_2O_3 (1.860 g) (96% D) and methyl 5-*exo*-2-norbornene carboxylate (1.00 mmol, 0.154 g) (isolated by prep GC on a 30% Carbowax 20M on Chromasorb W column). The slurry was allowed to stir at 60 °C (oil bath) for 24 h. After cooling, the alumina was extracted with acetone (4×20 mL) to afford, after concentration, 1.40 g (75%) of a mixture of esters. GC/MS analysis revealed a 90:10 mixture of *exo* and *endo* esters, neither of which contained deuterium. This was determined from the intensity of the M+1 mass peak (153 m/e) which was 10% of the molecular ion ($C_9H_{12}O_2$, 152 m/e) due to ^{13}C contributions. The isomer ratio was also verified by ^1H NMR.

The Reaction of Cyclopentadiene with Dimethyl Fumarate in Solution. In a 50-mL round-bottomed flask was placed, at 0 °C, dimethyl fumarate (7.50 mmol, 1.08 g) and cyclopentadiene (8.49 mmol, 0.560 g) in methylene chloride (10 mL). The reaction was maintained at 0 °C for 3 h and then at 25 °C for 5 h with stirring. Removal of the solvent *in vacuo* followed by chromatography (hexane/EtOAc 19:1) afforded 1.18 g (75%) of dimethyl *trans*-norbor-2-ene-5,6-dicarboxylate contaminated with a small amount of dimethyl fumarate as evidenced by GC/MS analysis: t_R = 6.44 min (dimethyl fumarate); t_R = 12.72 min (**7**). Dimethyl *trans*-norbor-2-ene-5,6-dicarboxylate (**7**): MS m/e (%) M^+ 210 (8), 179 (17), 145 (66), 113 (85), 91 (31), 66 (100); ^{1}H NMR ($CDCl_3$) δ 3.65 (s, 3H); 3.72 (s, 3H); 6.14 (m, 1H); 6.34 (m, 1H); ^{13}C NMR ($CDCl_3$) δ 174.9, 172.8, 137.8, 134.8, 51.4, 51.9, 47.6, 47.3, 46.9, 46.7, 45.3.

The Reaction of Dimethyl Fumarate with Methyl 5-*endo*-2-nobornene Carboxylate (1) on 400°-Al_2O_3. In a 50-mL round-bottomed flask was placed 400°-D/Al_2O_3 (12.0 g, 96% D) and dimethyl fumarate (3.81 mmol, 0.801 g) in ethyl ether (10 mL). The slurry was stirred at 25 °C for 10 min. The solvent was evaporated *in vacuo* at 25° and methyl 5-*endo*-2-nobornene carboxylate were added (3.82 mmol, 0.580 g) at 0°C. The solid was heated to 55 °C (oil bath) with continuous stirring for 24 h. The alumina was extracted with ether (5×20 mL) and the products concentrated *in vacuo*. Analysis by GC/MS and ^{1}H NMR indicated dimethyl *trans*-norbor-2-ene-5,6-dicarboxylate (**7**) in the products (20%). The identity of **7**

was verified by comparison of its ^{1}H and ^{13}C NMR spectra with those of an authentic sample.

Reaction of Cyclopentadiene with Methyl Acrylate on Deuterated and 400 °C Activated Alumina. To a 50-mL round-bottomed flask containing 96% deuterated alumina (12.0 g), that had been activated at 400 °C for 4 h, were added methyl acrylate (7.50 mmol, 0.645 g) and freshly distilled cyclopentadiene (8.30 mmol, 0.548 g). The slurry was allowed to stir at 70 °C for 1 h. After cooling, the products of the reaction were removed from the solid by extraction with anhydrous ether (5 × 20 mL), and analyzed by GC/MS for deuterium content: dicyclopentadiene (11%); 53% d_0, 16% d_1, 16% d_2, 10% d_3, 3.4% d_4, 1.4% d_5, and 0.6% d_6; methyl 5-*endo*-2-norbornenecarboxylate (89%); 49% d_0, 35% d_1, 12% d_2, 3.5% d_3, 0.3% d_4.

The method of calculation of deuterium content in the Diels-Alder adducts involves correction for isotopic abundances for the empirical formulas of the appropriate ion structures as reported (65). Thus, for the molecular ion ($C_9H_{12}O_2$, mass 152), the isotope correction for $(M+1)^+$ (mass 153) is 9.996% and for (M+2) (mass 154) is 0.8497%. Similarly, for the molecular ion ($C_{10}H_{12}$, mass 132) the isotope correction for $(M+1)^+$ (mass 67) is 10.998% and for $(M+2)^+$ (mass 68) is 0.5464%. For the cyclopentadiene ion (C_5H_6, mass 66), the $(M+1)^+$ (67) and $(M+2)^+$ (68) mass peaks are 5.499% and 0.122%, respectively, relative to the M^+ abundance mass peak (considered) 100 units.

Reaction of Cyclopentadiene with Dimethyl Fumarate on Deuterated and 400 °C Activated Alumina. To a 50-mL round-bottomed flask containing 96% deuterated alumina (16.0 g) that had been activated at 400 °C for 4 h were added dimethyl fumarate (7.50 mmol) and freshly distilled cyclopentadiene (8.30 mmol, 0.548 g). The slurry was allowed to stirr at 60 °C for 1 h. After cooling, the products of the reaction were removed from the solid by extraction with anhydrous ether (5 × 20 mL), and analyzed by GC/MS for deuterium content: dicyclopentadiene (9%); 6.6% d_0, 5.6% d_1, 9.2% d_2, 18.6% d_3, 22% d_4, 22% d_5, and 16% d_6; dimethyl *trans*-5,6-norborn-2-enecarboxylate (91%), 100% d_0.

Dimerization of Cyclopentadiene on Deuterated and 400 °C Activated Alumina. To a 50-mL round-bottomed flask containing 96% deuterated alumina (10.0 g) that had been activated at 400 °C for 4 h was added, freshly distilled cyclopentadiene (16.0 mmol, 1.06 g). The slurry was allowed to stirr at 60 °C for 1 h. After cooling, the products of the reaction were removed from the solid by extraction with anhydrous ether (5 × 20 mL), and analyzed by GC/MS for deuterium content: dicyclopentadiene (90%), 15% d_0, 29% d_1, 27% d_2, 19% d_3, 6.5% d_4, 1.8% d_5, and 1.7% d_6.

Reaction of Cyclopentadiene with Methyl Acrylate on 5 Å Zeolite Activated at 400 °C. To a 50-mL round-bottomed flask containing zeolite (5.80 g) that had been activated at 400 °C for 4 h were added methyl acrylate (7.50 mmol, 0.645 g) and freshly distilled cyclopentadiene (7.50 mmol, 0.495 g). The slurry was allowed to stir at 60 °C for 4 h. After cooling, the products of the reaction were removed

from the solid by extraction with anhydrous ether (5 × 20 mL) and analyzed by GC/MS in order to determine the *endo/exo* ratio (3.4) of the ester products. Evaporation of the solvent and purification by column chromatography (ether/hexane 1 : 30 as eluant) gave the Diels-Alder adducts **1** and **2** in 75% yield. This procedure was then repeated with a larger quantity of zeolite (11.7 g) to yield 70% of **1** and **2** in a 4.2 *endo/exo* ratio.

Reaction of Cyclopentadiene with Methyl Acrylate on 800 °C Activated Alumina. To a 100-mL round-bottomed flask containing alumina (17.3 g) that had been activated at 800 °C for 4 h were added methyl acrylate (7.50 mmol, 0.645 g) and freshly distilled cyclopentadiene (7.50 mmol, 0.495 g). The slurry was allowed to stir at 55 °C for 5 h. After cooling, the products of the reaction were removed from the solid by extraction with anhydrous ether (5 × 20 mL), and analyzed by GC/MS in order to determine the *endo/exo* ratio (0.93) of the ester products. Evaporation of the solvent and purification by column chromatography (ether/hexane=1 : 30 as eluant) gave the Diels-Alder adducts **1** and **2** in 55% yield. A small amount of 5-norbornene-2-carboxylic acid was also detected in the products (5%). In a separate experiment, into a 100-mL round-bottomed flask containing alumina (18.0 g) that had been activated at 800 °C for 4 h were added methyl acrylate (7.50 mmol, 0.645 g) and freshly distilled cyclopentadiene (7.50 mmol, 0.495 g). The slurry was allowed to stirr at 25 °C for 48 h. Periodically samples (0.2 g) were taken from the reaction mixture, washed with ether (10 mL),

and the *endo/exo* ratio of **1** and **2** monitored by GC/MS. At all times, the *endo/exo* ratio was found to be 0.91(±0.06).

Epimerization of Methyl 5-*endo*-2-Norbornene Carboxylate (1) to its *exo*-isomer (2) on 800 °C Alumina. The following is representative of the epimerization reactions run on alumina activated at 800 °C (Table 8, pg 34). In a 50-mL round-bottomed flask was placed, at 0° C, 800°-alumina (11.4 g), and methyl 5-*endo*-2-norbornenecarboxylate (7.50 mmol, 1.14 g) (isolated by prep GC on a 30% Carbowax 20M on Chromasorb W column). The reaction was allowed to stir for 3 h at 56 °C. After cooling, the solid was extracted with anhydrous ether (5 × 20 mL). GC/MS revealed a 46 : 54 mixture of **1** and **2**. Concentration *in vacuo* afforded a 80% recovery of esters. Following extraction, the recovered alumina, was dissolved in conc HCl (40 mL) with continuous stirring for 2 h. The resulting mixture was diluted with H_2O (80 mL), and extracted with ether (5 × 25 mL). The combined ether extracts were treated with $NaHCO_3$, dried over anhydrous $MgSO_4$, and analyzed by GC/MS. Evaporation of the solvent afforded 0.021 g of products.

Preparation of (*R*)-(-)-Menthyl Acrylate. Acryloyl chloride (32.6 mmol, 2.60 mL) was added slowly to a mixture of (-)-menthol (29.6 mmol, 4.62 g), triethylamine (32.6 mmol, 4.50 mL) and 4-(dimethylamino)pyridine (0.50 mmol, 0.06g) in methylene chloride (15 mL). The mixture was refluxed for 0.5 h and, upon cooling, 10% aqueous sodium bicarbonate (15 mL) was added. The organic layer was dried over anhydrous sodium sulfate and the solvent removed *in vacuo*. The

product was purified by distillation under vacuum (bp 102-104°, 11 mm Hg), and by column chromatography (hexane/EtOAc 80:1). Hydroquinone (0.3%) was added and the product stored in a freezer until used (70% yield). MS m/z(%): 195(89), 138(67), 123(42), 95(39), 55(100), 41(61).

Preparation of (-)-Menthyl Bicylo[2.2.1]hept-5-ene-2-Carboxylate. To a 25 mL round-bottomed flask containing (-)-methyl acrylate (4.10 mmol, 0.860 g), at 0°C, was added, under argon, freshly distilled cylcopentadiene (6.026 mmol, 0.50 mL). The reaction flask was raised to room temperature and allowed to stir for 6 h. The reaction mixture was then diluted with ether (10 mL). Capillary GLC analysis revealed a 73:27 mixture of *endo* and *exo* menthyl esters: t_R (menthyl-*exo*-bicylo[2.2.1]hept-5-ene-2-carboxylates **10a** + **10b**) = 15.10 min, t_R (menthyl-*endo*-bicyclo[2.2.1]hept-5-ene-2-(*S*)-carboxylate **11a**) = 15.37 min, t_R (menthyl-*endo*-bicyclo[2.2.1]hept-5-ene-2-(*R*)-carboxylate **11b**) = 15.56 min; *endo*-**11b**/*endo*-**11a** = 54:46. Evaporation of solvent and purification of the residue by column chromatography (hexanes/ether 450:1) gave the menthyl esters in 68% yield.

Preparation of *Endo*-bicyclo[2.2.1]hept-5-ene-2-methanol. To a 100-mL flask containing menthyl esters **10** and **11** (2.72 mmol, 0.75 g) in anhydrous ether (50 mL), was added $LiAlH_4$ (2.62 mmol, 0.100 g). The reaction was maintained at 25 °C for 10 h with stirring. The excess hydride was decomposed with saturated aqueous Na_2SO_4, dried over anhydrous $MgSO_4$ and the ether distilled. The resulting solution of isomeric bicyclo[2.2.1]hept-5-ene-2-carbinols was separated by preparative gas chromatography using a 30% Carbowax 20M on 60-80 mesh

Chromosorb W column maintained at 190 °C. The *endo* isomer's rotation was measured in 95% ethanol. The absolute configuration of the major *endo*-adduct **11b** ($[a]_{D25°}$ = +6.9° (*c* 1.0, 95%EtOH)) was determined to be *R* by comparison with the $[\alpha]_D$ value of an authentic sample (63). Since in 95% alcohol, $[a]_{D25°}$ = +76.6 for pure *endo*-bicyclo[2.2.1] hept-5-ene-2-(*R*)-methanol, the optical yield was calculated to be 9%. Analysis of the *endo*-adducts **11a + 11b**: ^{1}H NMR ($CDCl_3$) δ 0.54 (m, 1H) 1.1-1.6 (3H), 1.84 (m, 1H), 2.3 (m, 1H), 2.7-3.05 (2H), 3.1-3.6 (2H), 5.98 (dd, J=2.5,6,1H), 6.16 (dd, J=2.5,6,1H); MS 124 (4, $C_8H_{12}O^+$), 106(2), 91(8), 77(9), 66(100); ^{13}C NMR ($CDCl_3$) δ 137.18, 132.17, 66.16, 49.47, 43.62, 42.21, 41.62, 28.89; *exo*-adducts: ^{13}C NMR ($CDCl_3$) δ 136.58, 136.47, 67.27, 43.43, 41.83, 41.73, 41.56, 29.62.

Reaction of Cyclopentadiene with (-)-Menthyl Acrylate on Alumina. To a 250 mL round-bottom flask fitted with a condenser and stirring bar was added unactivated alumina (31.6 g) freshly prepared cyclopentadiene (7.38 mmol, 0.487 g), and (-)-menthyl acrylate (7.381 mmol, 1.550 g). The reaction was maintained at 65 °C (oil bath) for 5 h with stirring. After cooling, the mixture was extracted with acetone (5 × 30 mL), filtered through Celite, and concentrated *in vacuo* to afford 68 % of an 81:19 *endo:exo* mixture of esters as determined by GC. This mixture was dissolved in ether (50 mL) and $LiAlH_4$ (2.51 mmol, 0.0954 g) added. The reaction was maintained at 25 °C for 5 h and then quenched with saturated aqueous Na_2SO_4, filtered, dried over anhydrous $MgSO_4$, and concentrated *in vacuo* to afford a mixture of *endo* and *exo* bicyclo[2.2.1]hept-5-en-2-methanol (82%).

The isomeric alcohols were separated by preparative gas chromatography on a 30% Carbowax 20M on 60-80 mesh Chromosorb W column at 185 °C. The purity of the *endo* alcohol was established by ^{13}C NMR, ^{1}H NMR, and by GC. Examination by GC established that the *endo* alcohol (t_R = 5.42 min) was contaminated with a trace amount of (-)-menthol (t_R = 6.36 min). Analysis by 250 MHz ^{1}H NMR indicated that the amount of (-)-menthol present was 4%. The specific rotation of the collected mixture of *endo* alcohols, with the (-)-menthol impurity, was $[a]_D^{20°}$ = +9.05°(95% EtOH). This value was corrected for the presence of (-)-menthol as follows.

mf(-)menthol (-50°) + *mf*ROH (*R*) = observed specific rotation

$R = mfe_1\ (-76.6°) + mfe_2\ (+76.6°)$

$e_1 + e_2 = 1$

where *mf* is the mole fraction of respective compound and mfe_1, mfe_2 are the mole fractions of the enantiomers of the *endo* alcohol. This procedure was then repeated at 25 °C, 0 °C, -10 °C, -10 °C, and -78 °C, with aluminas which had been dehydrated at 400 °C, 600 °C, and 800 °C respectively.

Reaction of Cyclopentadiene with Methyl Acrylate on 400°-Alumina coated with (-)-Menthol. To a 250-mL flask containing alumina (23.0 g) that had been activated at 400 °C for 4 h was added a solution of (-)-menthol (0.296 mmol, 0.0460 g) in ethyl ether (50 mL). The slurry was stirred at room temperature for 45 minutes, and the solvent was removed using a rotoevaporator. To this modified alumina was added, at 0 C,° methyl acrylate (15.1 mmol, 1.30 g) and

freshly distilled cyclopentadiene (14.9 mmol, 0.990 g). The reaction was maintained at 65 °C for 4 h with stirring. After cooling, the products were removed from the solid by extraction with ether (5×20 mL). Evaporation of solvent and purification of the residue by column chromatography (hexanes/ethylacetate= 19:1) afforded a mixture of *endo* and *exo* esters (6.78 mmol, 1.03 g) in 46% yield. The esters were then reducted with $LiAlH_4$ (3.39 mmol, 0.129 g) in ether (50 mL) at room temperature for 5 h. Quenching of the mixture by addition of saturated aqueous Na_2SO_4, drying with anhydrous $MgSO_4$, and evaporation of the solvent *in vacuo* afforded a mixture of *endo* and *exo* alcohols (86%). Removal of the *exo* isomer by preparative gas chromatography (30% Carbowax 20M on Chromosorb W column at 185 °C) afforded the *endo* alcohols as a mixture of enantiomers (**11a**+**11b**) (3.120 mmol, 0.386 g) in 45% yield. In a 25-mL flask containing dicyclohexylcarbodiimide (1.089 mmol, 0.225 g) in CH_2Cl_2 (15 mL), was added at 25 °C, (*R*)-(+)-α-methoxy-α-(trifluoromethyl)phenylacetic acid (1.089 mmol, 0.2550 g) and a mixture of **11a** and **11b** (90 mg, 0.726 mmol), followed by 4-dimethylaminopyridine (0.0980 mmol, 0.0120 g). The reaction was maintained at 25 °C for 1 h with stirring. After 1 h the mixture was filtered and purified by column chromatography on alumina (CH_2Cl_2 as eluant) to afford an inseparable mixture of diastereomeric (+)-MTPA esters (0.508 mmol, 0.173 g) 70% yield: ^{1}H NMR ($CDCl_3$) δ 0.4-2.8 (m, 4H), 2.82 (m, 2H), 3.56 (s, 3H), 3.9-4.4 (d, 2H), 5.92 (m, 1H), 6.18 (m, 1H), 7.3-8.2 (m, 5H); ^{19}F NMR in a $Eu(fod)_3$:(+)-MTPA-esters= 0.86 (mol/mol) complex signal of (*R*)-

MTPA was 0.21 ppm upfield from that of (*S*)-MTPA isomer. This procedure was then repeated with aluminas that had been coated with 0.120 g, 0.233 g, 4.60 g, and 11.5 g, of (-)-menthol respectively.

Reaction of Cyclopentadiene with (-)-Menthyl Acrylate on 400°-Alumina Coated with (-)-Menthol. To a 250-mL flask containing alumina (31.14 g) that had been activated at 400 °C for 4 h was added a solution of (-)-menthol (19.9 mmol, 3.11 g) in ethyl ether (80 mL). The slurry was stirred at room temperature for 20 minutes, and the solvent was carefully removed *in vacuo*. To this alumina, was added at 0° C (-)-menthyl acrylate (7.50 mmol, 1.58 g) and freshly distilled cyclopentadiene (7.50 mmol, 0.495 g). The reaction was maintained at 60 °C for 4 h with stirring. After cooling, the products were removed from the solid by extraction with ether (4×50 mL). Evaporation of solvent and purification of the residue by column chromatography (ether/hexane = 1:30 as eluant) afforded a mixture of *endo* and *exo* esters (4.13 mmol, 1.14 g) in 55% yield. The esters were reduced with $LiAlH_4$ (2.10 mmol, 0.080 g) in ether (30 mL) at room temperature for 1 h. The mixture was quenched by addition of saturated aqueous Na_2SO_4, dried over anhydrous $MgSO_4$, and the solvent evaporated *in vacuo* to afford a mixture of *endo* and *exo* alcohols (70 %). Removal of the *exo* isomer by preparative gas chromatography (30% Carbowax 20M on Chromosorb W column at 185 °C) afforded the *endo* alcohols as a mixture of enantiomers (**11a + 11b**). The optical yield was calculated to be 24% ee by measuring its optical rotation: $[\alpha]_{D25°} = +12.9°$ (*c* 1, EtOH).

Reaction of Cyclopentadiene with (-)-Menthyl Acrylate on 400°-Alumina Coated with (*L*)-(+)-Glutamic acid. To a 100-mL flask containing alumina (23 g) that had been activated at 400 °C for 4 h was added, a solution of (*S*)-(+)-glutamic acid (7.75 mmol, 1.14 g) in ethyl ether (50 mL). The slurry was stirred at room temperature for 30 minutes, and the solvent was removed on a rotoevaporator. To this alumina, was added at 0° C menthyl acrylate (5.50 mmol, 1.15 g) and freshly distilled cyclopentadiene (5.76 mmol, 0.38 g). The reaction was maintained at 60 °C for 4 h with stirring. After cooling, the products were removed from the solid by extraction with ether (4×50 mL). The *endo* to *exo* ratio of esters was established by GC analysis. The products of the reaction, without further isolation, was reduced with a large excess of $LiAlH_4$ (7.70 mmol, 0.294 g) in ether (50 mL) at room temperature for 5 h. Quenching of the mixture by addition of saturated aqueous Na_2SO_4, drying with anhydrous $MgSO_4$, and evaporation of the solvent *in vacuo* afforded a mixture of *endo* and *exo* alcohols (80%). The *endo* isomer was isolated by preparative gas chromatography (30% Carbowax 20M on Chromosorb W column at 185 °C) and its rotation was measured: $[\alpha]_{D25°} = +12.9°$(*c* 1, EtOH).

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