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BORAHETEROCYCLES VIA CYCLIC HYDROBORATION

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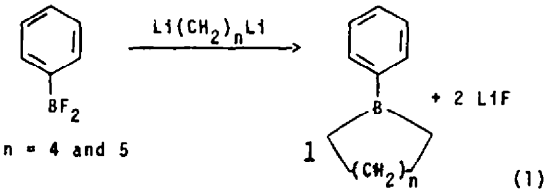
Abstract—The cyclic hydroboration of dienes and polyenes provides a valuable route to organoborane heterocycles. Many of these provide interesting new organic structures for study. Some of these derivatives have proven to be highly useful new reagents for organic synthesis. Finally, the ready conversion of such organoboranes to other organic derivatives provides a valuable new means for achieving stereochemical control in synthesis and in providing a versatile new route to carbon ring derivatives.

I. INTRODUCTION

Organoborane heterocycles may be defined as those cyclic species which contain at least one endocyclic B–C bond. Although a number of boron-containing heterocycles have been known for many decades,[1] the chemistry of organoborane heterocycles is of relatively short history, and the first reported synthesis of organoborane heterocycles was described by Torssel[2] only in 1954 (eqn 1).



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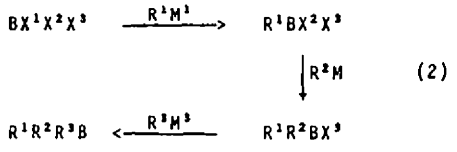
Hydroboration,[3,4] discovered in 1956, has made various types of organoboranes readily available and has triggered systematic explorations of their chemistry. The results obtained mainly within the past decade clearly indicate that the organoboranes are a class of highly unique and versatile reagents and intermediates in organic synthesis.[4]

This review primarily deals with those organoborane heterocycles which are obtainable via cyclic hydroboration of dienes, trienes, and related species with either certain complexes of borane itself (BH_3), such as borane-tetrahydrofuran[5] and borane-methyl sulfide,[5] or monosubstituted boranes (XBH_2). Some of the initial results were discussed in an earlier review in 1972,[6a] and a brief updated summary of cyclic hydroboration was recently presented.[6b] In the present report we present a more detailed comprehensive treatment with special emphasis on various unique applications of the organoborane heterocycles as reagents and intermediates in organic synthesis.

Although no detailed discussion is appropriate here, it should be pointed out that there exist other methods for the preparation of organoborane heterocycles other than hydroboration.[7] These may be briefly described for comparison with the hydroboration procedure which is the central theme of the present treatment.

1. *Transmetallation*[7]

The general scheme of the transmetallation approach is shown in eqn (2), and the reaction shown in eqn (1) exemplifies its application to the synthesis of organoborane heterocycles. When M = Li or MgX and X = halogen, the reaction usually proceeds rapidly, even at low temperatures (< 0°C).



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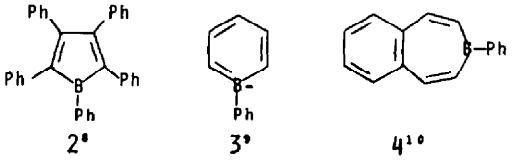
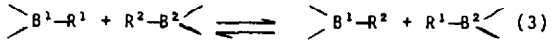
A number of theoretically interesting organoborane heterocycles, such as **2**–**4**, have been prepared by this method.[8–10]



2[8] **3**[9] **4**[10]

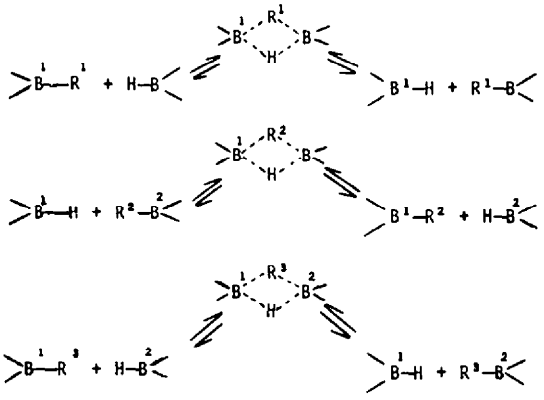
2. *Disproportionation*[7,11]

The disproportionation reaction, which may be represented by eqn (3), has been applied extensively to the synthesis of organoborane heterocycles.[11] Until the cyclic hydroboration method[6] was developed as a more



(3)

direct route, the disproportionation reaction had probably been most estensively utilized as a method for the preparation of organoborane heterocycles.[11] The reaction is markedly catalyzed by boron hydrides and organoalanes, and generally proceeds readily at room temperature or even at 0°C in the presence of a suitable catalyst. Although not yet established, the following mechanism involving the four-center transition states appear consistent with the results obtained with boron hydrides as catalysts.



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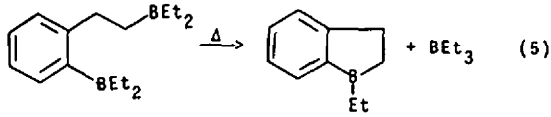
The success observed in applying this method to the synthesis of cyclic organoboranes, as exemplified in eqn (5), appears to depend, at least in part, on (a) the stability with respect to disproportionation of the cyclic product relative to the acyclic starting organoborane and (b) the formation of a product, desired compound or undesired side-product such as triethylborane, which can be removed from the reaction system by distillation or some



(5)

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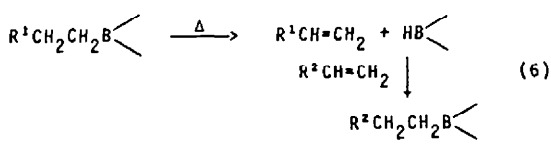
other means. For further discussion, readers are referred to the reviews by Köster,[11] although they should be cautioned that a number of the structures presented in these articles have since been revised, as described in detail later in this review.

3. *Displacement*[3,4,6,11]

The displacement reaction between organoboranes and olefins appears to involve the dehydroboration-hydroboration sequence[3] shown in eqn (6), which has been applied to the synthesis of organoborane heterocycles, as exemplified by eqn (7). The reaction is generally carried out at elevated temperatures (> 50°C).



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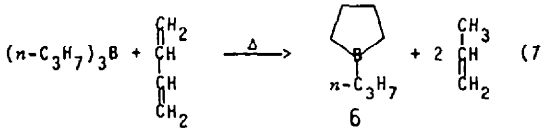

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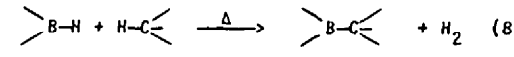
4. *Substitution*[4,11,12]

The substitution reaction in this review refers to the irreversible reaction represented by eqn (8). Usually, the boron hydride species is generated *in situ* via de-



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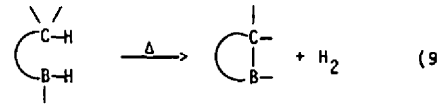
hydroboration at elevated temperatures. Although the intermolecular substitution reaction has largely been restricted to aromatic hydrocarbons, a number of intramolecular substitution reactions have been observed even with aliphatic derivatives (eqn 9). One of the drawbacks associated with this reaction is that it usually



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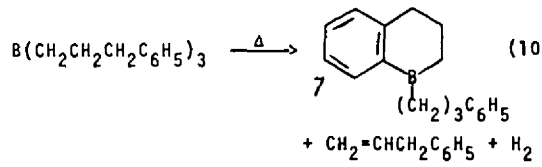
proceeds at reasonable rates only above 200°C. Even so, it seems to be the method of choice for the preparation of certain arylborane heterocycles[11] (eqn 10). Another potential advantage lies in the fact that monoenes and



(10)

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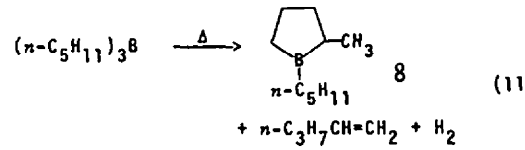
dienes, which are often more readily available than the corresponding dienes and trienes, can be used as starting materials for the synthesis of mono- and bicyclic organoboranes respectively (eqns 11 and 12).



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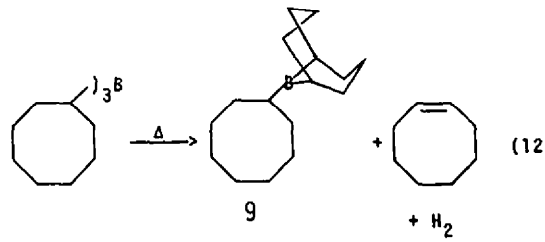

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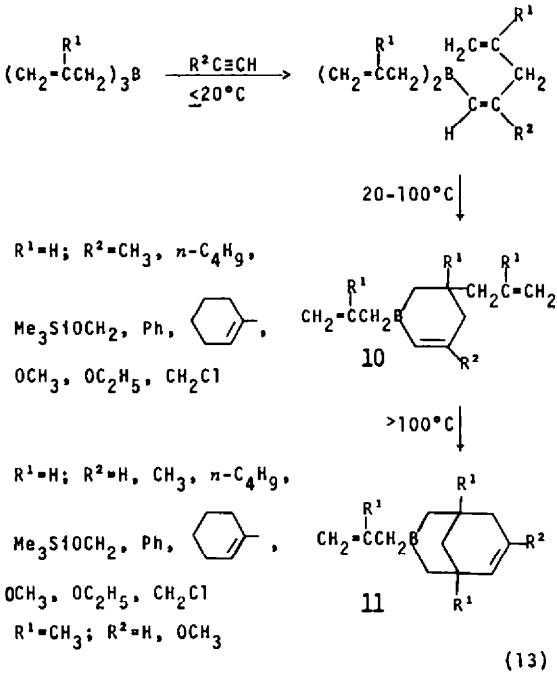
5. *Allylboration*[13]

Unlike organoalanes,[7b,c] organoboranes do not readily participate in the carbometallation reaction. Allylboranes are, however, exceptional and react with acetylenes and olefins to form the corresponding addition products,[13] as exemplified by the transformation shown in eqn (13).

For the formation of **10**, the 6-center transition state **12** has been suggested.[13]

An interesting extension is the following preparation of 1-boraadamantane[14] and its conversion to 1-adamantanol via carbonylation-oxidation[15,16] (eqn 14).

The synthetic methods available at the present time, including the cyclic hydroboration route, are often



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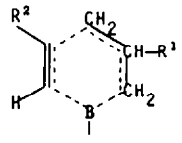

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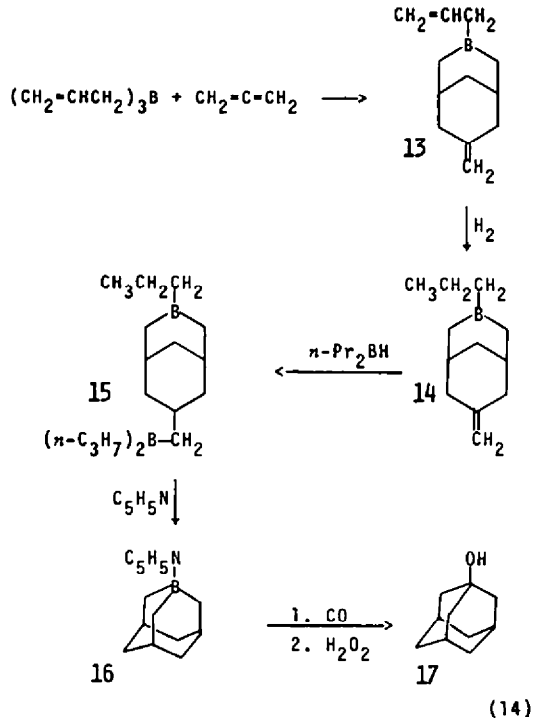


(14)

complementary to one another. However, in cases where the cyclic hydroboration reaction is applicable, it is usually the method of choice, since it is, in most cases, simpler and more convenient than the other methods.

In order to keep this review within a manageable length, those organoborane heterocycles which contain one or more endocyclic hetero atom–boron bonds, such as the extensive series of aromatic borazaro compounds studied by Dewar,[17] are not included in the present discussion. Also excluded is the chemistry of carboranes, for which several extensive reviews are available.[18]

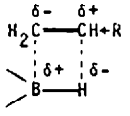
II. REGIOCHEMISTRY (DIRECTIVE EFFECTS) AND STEREOCHEMISTRY OF CYCLIC HYDROBORATION

Prior to the development of some recent techniques to be discussed later (Section III), the hydroboration of dienes and polyenes was investigated mainly by analyzing the products obtained after the oxidation of the organoborane intermediates with alkaline hydrogen peroxide.[3] Although the analysis of the oxidation products does not generally permit a distinction between cyclic species and polymeric species, it establishes unequivocally the regiochemistry (directive effects) and stereochemistry of the hydroboration of dienes and polyenes.

In this section, the regiochemical and stereochemical results are summarized and discussed.

Just as in electrophilic aromatic substitution reactions, the hydroboration reaction involves the interaction of carbon–carbon double bonds with the electrophilic boron hydride species. As might be expected, the reaction is influenced by (a) inductive (+I and −I), (b) resonance (+R and −R), and (c) steric (S) effects (IRS effects).

The regiochemistry (directive effects) observed with monoenes have been well delineated and reasonably well understood.[3] The boron–hydrogen bond is presumably polarized with the hydrogen having some hydridic character. In addition, the boron-containing moiety is clearly sterically more demanding than the hydrogen. Thus, the anti-Markovnikov addition of the B–H bond observed with simple alkenes is readily attributable to a combination of the electronic and steric effects exerted by the alkyl substituents.



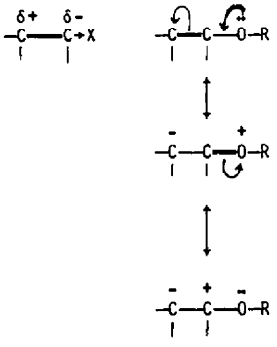
Some representative results pertinent to the present discussion are summarized below (R^1, R^2 and R^3 are alkyl groups).

	H_2C—CHR^1		H_2C—CR^1R^2		R^1HC—CR^2R^3	
	↑	↑	↑	↑	↑	↑
BH_3·THF[19]	94	6	99	1	98	2
$ClBH_2$·OEt_2[20]	>99.5	<0.5	>99.9	<0.1	99.7	0.3
	94-95	5-6				
Sia_2BH[3]	99	1	>99	<1	>99	<1

Hetero-substituents on or near the carbon–carbon double or triple bond can exert strong directive influences. For example, the hydroboration of vinyl halides places the B atom predominantly on the α-C atom,[22] whereas the alkoxy group, which is directly bonded to the olefinic carbon, strongly directs the boron to the β-position.[22b] Some representative results obtained with borane–THF are shown below.

$CH_3CH_2CH{=}CHCl$	$CH_3CH_2CH{=}CHOEt$
15 85	~100 ~0
$(CH_3)_2C{=}CHCl$	$(CH_3)_2C{=}CHOEt$
~0 ~100	~100 ~0

On a qualitative basis, these results are readily interpreted on the reasonable assumption that the −I effect is more significant than the +R effect in the cases of vinyl halides, whereas the hydroboration of enol ethers is totally dominated by the +R effect.



There is little doubt that these IRS effects are also operating in the hydroboration of dienes and polyenes. However, it has also become evident that some additional effects operate in such cases. When the two or more carbon–carbon double bonds within a diene or polyene molecule are isolated, differences are often observed between the regiochemistry realized and that predicted from the behavior of related monoenes. Such differences are attributable to the cyclic nature of hydroboration of such dienes or polyenes.[23]

Some representative results of the hydroboration-oxidation of dienes are summarized in Table 1.

1. *Conjugated dienes*

In the conjugated dienes, the reactivity of one carbon-carbon double bond is strongly influenced by the I and R effects exerted by the other. The hydroboration-oxidation of 1,3-butadiene[24–30] with borane–THF produces 1,3- and 1,4-butanediols in a 30:70 ratio, irrespective of the reactant ratio and the mode of addition. The amount of the 1,3-diol is considerably greater than that expected from the 94:6 ratio observed in simple monosubstituted terminal monoenes. Since it is highly unlikely that 4-membered ring formation is competitive with 5-membered ring formation in such cases, we tentatively attribute this abnormal diol ratio to the electron-withdrawing effect of the C=C double bond.

$\overset{\delta+\ \ \delta-}{CH_2{=}CH{-}CH{=}CH_2}$

	$CH_2{=}CH{-}CH{=}CH_2$	$CH_2{=}C(CH_3){-}CH{=}CH_2$	$CH_2{=}C(CH_3){-}C(CH_3){=}CH_2$
1,4-	ca. 70%	87%	ca. 100%
1,3-	ca. 30%	13%	ca. 0%

The directive influence exerted by the C=C double bond is readily offset by introduction of the methyl group. Thus, 2,3-dimethyl-1,3-butadiene is converted nearly exclusively to the 1,4-diol.[24]

2. *1,4-Pentadienes and 1,5-hexadienes*

The hydrobotation-oxidation of 1,4-pentadiene with borane–THF produces 1,5- and 1,4-pentanediols in a ratio of *ca.* 45:55.[31] Although the ratio varies considerably, similar abnormal results have been observed also with thexylborane[21] and chloroborane.[32] These results cannot be readily accounted for by the IRS effects, since the electronic and steric effects of the alkyl group are expected to be similar to those of a simple alkyl group. Thus the results suggested to us that these reactions might be highly cyclic. Indeed, as discussed later in detail (Section IV), the hydroboration of 1,4-pentadiene with either borane–THF[31] or thexylborane[33b] has proved to be highly cyclic, although the relatively low yield of the cyclic organoborane observed with chloroborane-ethyl ether is somewhat puzzling.[32] The results realized with thexylborane clearly indicate that there exists a strong kinetic preference for the formation of a 5-membered ring over the corresponding 6-membered ring, despite the fact that formation of a 5-membered ring must direct the boron atom to one of the internal carbons. Although less noticeable, a similar tendency has also been observed with 1,5-hexadiene.[21,24,33,34] Thus, hydroboration of 1,5-hexadiene with thexylborane, followed by oxidation, gives 1,5- and 2,5-hexanediols in a ratio of 2:8, along with 1,6-hexanediol formed in 90% yield. These abnormal directive effects are once again entirely circumvented by placing two Me groups on the two internal olefinic C atoms, as revealed by the results realized with 2,4-dimethyl-1,4-pentadiene and 2,5-dimethyl-1,5-hexadiene.[39]

3. *1,6-Heptadiene, 1,7-octadiene, and higher dienes*

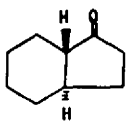
Directive effects observed with 1,6-heptadiene and 1,7-octadiene are as predicted based on the findings with monoenes.[32] Virtually no data regarding the hydroboration of higher α,ω-dienes exist (1,13-tetradecadiene has been hydroborated with chloroborane-ethyl ether[32]). However, we predict that the diol distribution pattern for these dienes should be similar to those for 1,6-heptadiene and 1,7-octadiene.

Hydroboration of cyclic and "mixed" dienes invariably involves not only regiochemistry but stereochemistry. The stereochemical results are considered next.

4. *1-Alkenylcycloalkenes*

Although no detailed study of the hydroboration oxidation of 1-alkenylcycloalkenes has been made, the reaction of several representative 1-alkenylcycloalkenes with thexylborane has produced organoborane intermediates, which on carbonylation, have been converted to bicyclic ketones **18–22** (54–73% yield).[42] Therefore, the intermediate organoboranes must have the structure represented by **23**.

Under conditions which do not epimerize the ketone products, they are 100% *trans*, indicating that the organoborane intermediates must also be 100% *trans*. It should be noted, however, that the *trans* geometry of these organoboranes has nothing to do with the cyclic nature of the hydroboration. Rather, it is merely an expected consequence of the exclusively *cis* nature of the hydroboration reaction itself. Thus, regardless of whether the reaction is cyclic or not, the hydroboration of 1-alkenylcycloalkanes will result in the formation of the *trans* isomers (eqns 15 and 16).



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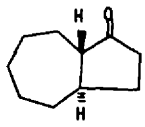
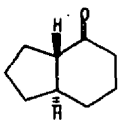
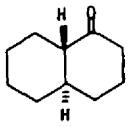


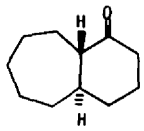
19 (71%)



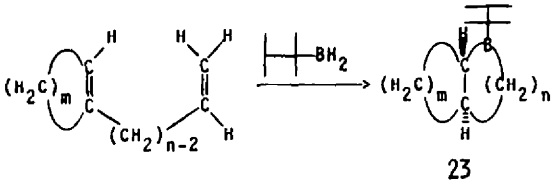
20 (54%)



21 (73%)



22 (68%)



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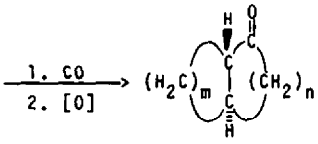

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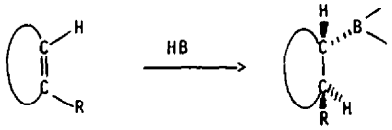


(16)

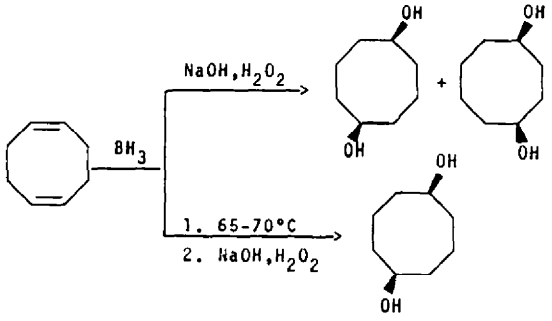
5. *Other alkenylcycloalkenes and cyclodienes*

Unlike the fused bicyclic organoboranes which, on the basis of the thermodynamic stability, are capable of attaining either the *cis* or the *trans* fused structure, the non-fused bicyclic organoboranes are expected to exist exclusively, or nearly exclusively, in the *cis* form, unless the size of one or both rings are large enough to accommodate the *trans* geometry. Although the critical number of ring atoms for such a transition is not known, it must be larger than seven.

The results of the hydroboration-oxidation of several representative cyclic and "mixed" dienes, summarized in Table 1. indicate the following.

1,4-*Cyclohexadiene.* Hydroboration of 1,4-cyclohexadiene with borane–THF[33] is neither stereoselective nor regioselective, producing mixtures of *trans*-diols and *cis*-diols in 29% and 48% combined yields, respectively. As discussed above, the formation of the monomeric bicyclic organoboranes corresponding to the *trans*-diols appear extremely unlikely. Therefore, the *trans*-diols must have been formed from some polymeric organoboranes. If so, the extent of the cyclic hydroboration cannot exceed 48%. This point will be discussed further in Section 3.

1,5-*Cyclooctadiene.* In marked contrast to the case of 1,4-cyclohexadiene, hydroboration of 1,5-cyclooctadiene with either borane–THF[33a,40] or thexylborane[33b] is highly stereoselective, producing the *cis*-diols in >90% yield. Although the reaction is not regioselective, thermal treatment of the hydroboration mixture at elevated temperatures (>50°C) can convert essentially all of the 1,4-isomer into the 1,5-isomer (eqn 17).



(17)

The hydroboration-thermal treatment-oxidation sequence provides a simple and selective synthesis of *cis*-1,5-cyclooctanediol from 1,5-cyclooctadiene. Although yet to be tested, other cyclooctadiene isomers, such as the 1,3- and 1,4-isomers, may also be used as starting compounds.

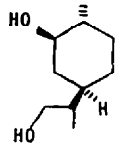
The ratios of 1,4- and 1,5-cyclooctanediols observed with borane–THF and thexylborane are worth noting. With thexylborane, the ratio is 78:22 in favor of the 1,4-diol. This is in agreement with the above presented generalization that, other things being comparable, the formation of the 5-membered organoborane is more favorable than that of the 6-membered organoborane. On the other hand, the ratio observed with borane–THF is 28:72 in favor of the 1,5-diol. The results are somewhat puzzling in light of the results observed with thexylborane. However, in view of the remarkably facile nature of the isomerization observed with 1,5-cyclooctadiene, the possibility that the 28:72 ratio may not represent the true kinetic ratio cannot be ruled out at this point.

4-*Vinylcyclohexene and limonene.* Hydroboration-oxidation of 4-vinylcyclohexene (**25**) is neither stereoselective nor regioselective. All four *cis*- and *trans*-isomers of 3- and 4-hydroxycyclohexaneethanols, as well as the *cis*-isomers of 3- and 4-hydroxy-α-methylcyclohexanemethanols, are formed in significant quantities, of which the *cis*-4-hydroxycyclohexaneethanol is the most abun-

25

26

dant.[33a] Here again, introduction of two Me groups in the strategic positions greatly simplifies the results. Thus, hydroboration-oxidation of D-(+)-limonene (**26**) with borane–THF produces essentially two diols, **27** and **28**, in a ratio of 76:24.[41]



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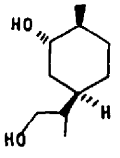

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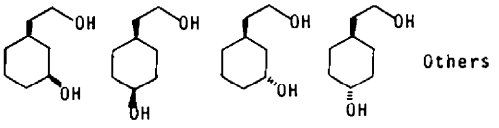
Table 1. Hydroboration-oxidation of dienes

Diene	Reagent	Conditions	Yield of diols,[a] %				Reference
			1,4-	1,3-	1,2-	Total	
1,3-Butadiene	BH_3:THF	3:2,0°C,THF	52(65)	25(31)	3(4)	80	24
		1:1,0°C,THF	56(76)	18(24)	trace	76	24
		1:2,0°C,THF	60(14)	34(36)	trace	94	25
	B_2H_6	3:2,ether pentane	—(55)	—(39)	—(6)	—	26
	Thexylborane	1:1,0°C,THF	—(79)	—(21)	—	—	21
	$ClBH_2 \cdot OEt_2$	1:1,0°C,ether	75(78)	21(22)	trace	96	23
	Sia_2BH	1:2,0°C,THF	70(90)	8(10)	—	78	30
2-Methyl-1,3-butadiene	$BH_3 \cdot THF$	3:2,20-25°C,THF	59(87)	9(13)	—	68	24
2,3-Dimethyl-1,3-butadiene	$BH_3 \cdot THF$	1:1,20-25°C,THF	66(100)	0(0)	0(0)	66	24
	Thexylborane	1:1,0°C,THF	89(100)	0(0)	0(0)	89	33b
			1,5-	1,4-	Others	Total	
1,4-Pentadiene	$BH_3 \cdot THF$	3:2,20-25°C,THF	—(38)	—(62)	—	—	24
		3:2,0°C,THF	42(45)	52(55)	—	94	31
		1:1,0°C,THF	39(42)	54(58)	—	93	31
		3:2,0°C,then 170°C,6 h	77(79)	13(13)	8(8)	98	31
	Thexylborane	1:1,0°C,THF	—(30)	—(70)	—	—	21
	$ClBH_2 \cdot OEt_2$	1:1,ether	—(47-43)	—(53-57)	—	—	23,32
	Sia_2BH	1:2,0°C,THF	71(85)	13(15)	—	84	30
2,4-Dimethyl-1,4-pentadiene	$BH_3 \cdot THF$	1:1,0°C,THF	97(98)	2(2)	—	99	33
			1,6-	1,5-	Others	Total	
1,5-Hexadiene	$BH_3 \cdot THF$	3:2,0°C,THF	—(69)	—(22)	—(9)	—	24
		1:1,0°C,THF	70(71)	24(24)	5(5)	99	34
	Thexylborane	1:1,0°C,THF	—(90)	—(2)	—(8)	—	33b
	$ClBH_2 \cdot OEt_2$	1:1,0°C,ether	—(74)	—(16)	—(10)	—	29
			—(93)	—(6)	—(1)	—	32
	Sia_2BH	1:2,0°C,THF	67(93)	—	5(7)	72	30
2,5-Dimethyl-1,5-hexadiene	$BH_3 \cdot THF$	1:1,0°C,THF	84(86)	—	14(14)	98	33
	$ClBH_2 \cdot OEt_2$	1:1,0°C,ether	—(99)	—	—	—	32
			1,7-	1,6-		Total	
1,6-Heptadiene	$ClBH_2 \cdot OEt_2$	1:1,0°C,ether	—(98)	—(2)		—	32
			1,8-	1,7-		Total	
1,7-Octadiene	$ClBH_2 \cdot OEt_2$	1:1,0°C,ether	—(99)	—(1)		—	32
			Monool	Diol	Δ^3-Cyclopentenol	Δ^2-Cyclopentenol	
Cyclopentadiene	$BH_3 \cdot THF$	2:1,0°C,THF	34	26.5	97	3	33c
	Thexylborane	2:1,0°C,THF	49.2	27	98.9	1.1	33c
	Sia_2BH	2:1,0°C,THF	64.1	14	99.0	1.0	33c
	IPC_2BH	2:1,0°C,THF	83	7.5	100	0	33c
			cis-1,3-	*cis*-1,4-	*trans*-1,3-	*trans*-1,4-	
1,4-Cyclohexadiene	$BH_3 \cdot THF$	1:1,0°C,THF	—(20)	—(28)	—(22)	—(30)	33d

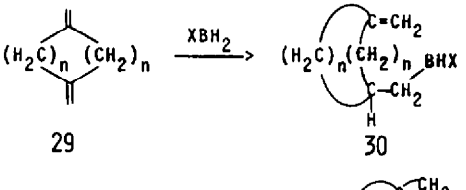
Table 1. (*Contd.*)

Diene	Reagent	Conditions	Yield of diols,[a] %					Reference
			cis-1,5-	*cis*-1,4-			Total	
1,5-Cyclooctadiene	BH_3·THF	1:1,0°C,THF	—(72)	—(28)			—	33a
			67(70)	29(30)			96	
			 Others					
4-Vinylcyclohexene	BH_3·THF	1:1,0°C,THF	—(10)	—(38)	—(13)	—(16)	—(23)	33a
				cis-2,9-	*trans*-2,9-		Total	
D-(+)-Limonene	BH_3·THF	3:2,0°C,THF		70(70)	30(30)		100	41
		1:1,0°C,THF		69(70)	30(30)		99	41
	Thexylborane	1:1,0°C,THF		76(84)	14(16)		90	41
		1:1,0°C,THF (simultaneous addition)		84(88)	12(12)		96	41

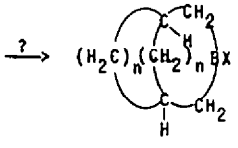
[a]The numbers in parentheses are diol distributions (%).

The *trans*-isomer must have been formed by some kind of acyclic hydroboration. The ratio of **27** to **28** observed with thexylborane is 85:15.[41] As discussed later, the *cis*-diol, **27**, can be obtained as the only product by oxidation of the distillate of the hydroboration product from limonene and thexylborane.[41] This demonstrates another unique application of cyclic hydroboration to selective organic synthesis.

Although not yet tested, it would be of interest to examine the hydroboration of dienes of the structure shown by **29**, which contain two exocyclic double bonds (eqn 18). If ring closure of the presumed intermediate **30**

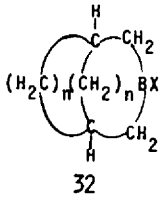


29 **30**



31 (18)

were to involve a cyclic hydroboration proceeding through the usual *cis*-addition, the bicyclic products, **31**, if they are formed, must be the in,out-isomers. However, it is also conceivable that the out,out-isomers, **32**, may result via polymerization-disproportionation.



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6. *Cyclic polyenes*

1,5,9-Cyclododecatriene appears to be the only cyclic polyene that has been subjected to hydroboration. Although no clear-cut results appear available for analysis of the triols, the course of the hydroboration and the identity of the organoborane products are now well delineated.[43,44] The original structural assignments by Köster[45] that the initial thermal product is the all *cis*-isomer, while the thermodynamically more stable product obtainable by a further thermal isomerization is the *cis,trans*-isomer, were seriously questioned by us[43] during the course of our study of the carbonylation of the initial product **33**. Our subsequent ^{1}H NMR study of the pyridine derivatives of **33** and **34** has clearly established the current, revised structural assignments shown in eqn (19).

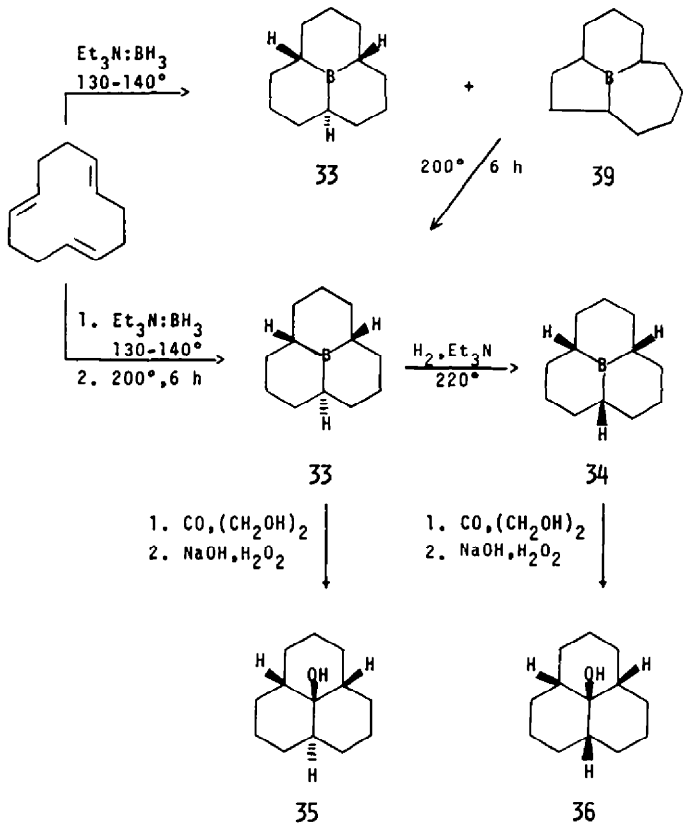
In addition to the fact that **33** and **34** have been converted via carbonylation-oxidation to **35** and **36**, respectively, their pyridine adducts **37** and **38** exhibit two and zero shielded methine protons, respectively.

If the thermal treatment at 200°C is omitted, the product is a mixture of **33** and its isomer to which Köster[45] tentatively assigned the structure **39**. Although reasonable, this structural assignment appears at best tenuous and its stereochemistry is yet to be determined.

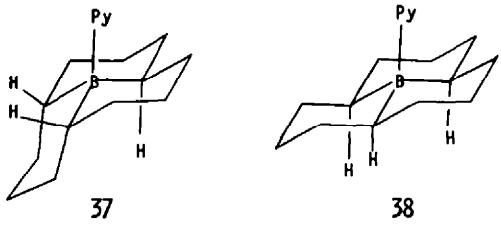
Borane–THF can also be used for hydroboration. Although similar results have been realized, the initial product is a white solid insoluble in organic solvents. It is, therefore, more difficult to handle.[44b] The product distribution realized with *trans,trans,cis*-cyclododecatriene is somewhat different, but the borane product can largely be converted to **33** or **34** in an analogous manner.[44b]

III. STRUCTURE OF ORGANOBORANE HETEROCYCLES

Borane complexes, such as borane–THF or borane–triethylamine, can act as trifunctional hydroborating agents. Thus, their reaction with dienes and polyenes can, in principle, produce an infinite number of products



(19)



37 38

of varying degrees of polymerization, including 3-dimensional network polymers. All of these conceivable products can be converted to the same set of isomeric alcoholic products on oxidation. Therefore, the regiochemical and stereochemical results presented in the previous sections do not permit determination of the organoborane structures, although they have provided suggestive data. To make the matter worse, organoboranes are generally considerably more labile than the corresponding carbon compounds, both chemically and thermodynamically. Many of the classic techniques for structural characterization and identification are often not realily applicable. As a consequence, much confusion and speculation as to the precise structures of the products produced in the hydroboration of dienes has existed until recently. It is therefore advisable to interpret with caution earlier results which were often not adequately supported by reliable experimental evidence. In this review, we have attempted as much as possible to distinguish speculation from well-established findings. However, reasonable interpretations that are only indirectly supported by experimental results are included in order to build up a coherent picture of cyclic hydroboration which hopefully is applicable to understanding and predicting results realizable with other dienes and polyenes.

A. METHODS OF ANALYSIS

Until recently, analysis of the oxidation products, along with more usual spectroscopic methods, such as IR, ^{1}H NMR and mass spectroscopy, had been commonly used for the identification and characterization of organoborane heterocycles and the estimation of their quantities in the reaction mixtures. As already mentioned, glc examination of the oxidation products does not generally permit a distinction between cyclic and polymeric species. Although the commonly used spectroscopic methods can be highly useful in identifying isolated organoborane heterocycles whose degrees of polymerization are known, they tend to be relatively useless for handling the complex reaction mixtures often formed in the hydroboration of dienes, especially for estimating the amounts of organoborane heterocycles present. This constitutes a frustrating problem, since isolation of organoboranes by distillation or glc separation is often accompanied by their decomposition via depolymerization, disproportionation, and so on, reactions which take place much more readily than those of the corresponding carbon analogs.

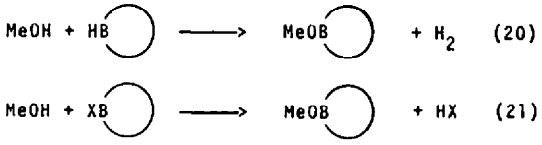
Fortunately, this situation has been largely resolved within the past several years by the development of reliable analytical techniques.

1. *Low temperature glc examination*

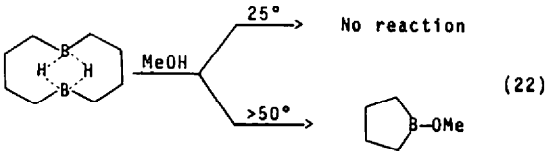
Just as in any other thermal techniques, glc examination can be complicated by decomposition of labile organoboranes. However, this problem can be overcome in many cases by controlling the temperatures of the injection block, column, detector, etc. In cases where decomposition is a problem, the amounts of the cyclic species should change as the temperature of the glc analysis is varied. As the temperature is decreased, one

reaches a point below which the amounts of cyclic species no longer change significantly. Glc analysis performed below this critical temperature should then be free of complications from decomposition. A case in point is the glc analysis of the methanolysis product of the organoborane produced in the hydroboration of 1,3-butadiene with borane-THF in a 1:1 molar ratio.[25b] At the injection block temperature of 150°, the amount of B-methoxyborolane corresponds to a yield of 70%. At 50°, however, no more than traces of B-methoxyborolane are detected, even though the compound is realily observable under these conditions. We therefore conclude that the reaction mixture does not contain any significant amount of B-methoxyborolane as such and that the B-methoxyborolane observed at higher block temperatures must be a thermal redistribution product. Of course, the same principle should also be applicable to examination of the reaction product by distillation, but such an operation would be far more time-consuming and therefore less practical.

In cases where the cyclic organoboranes are highly labile dialkylboranes[46] or B-haloboracyclanes, as in the above example, it is possible to convert such derivatives to the corresponding B-methoxy derivatives, and such B-OMe derivatives are more conveniently analyzed by glc (eqns 20 and 21). Both of these methanolysis reac-



tions are generally quite rapid, even at low temperatures, and there has been little or no indication that these methanolyses are complicated by depolymerization, isomerization, or any other side reactions at or below room temperatures. However, some dialkylborane derivatives have been encountered which do not react readily with methanol, as in eqn (22). Fortunately, such dialkylboranes are highly stable, both chemically and thermally, so that their direct glc examination is usually feasible.

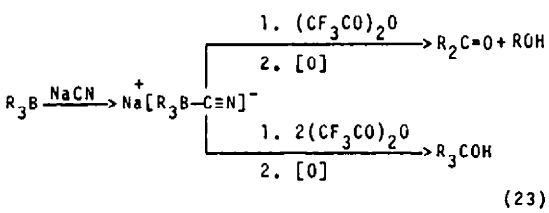


Use of nonpolar packing materials, such as SE-30, is recommended, as they tend to be chemically more inert. However, relatively polar columns, such as Carbowax 20M, can produce more satisfactory results with trialkylboranes of relatively high molecular weights.

To realize reproducible results, it is essential that the glc system be pre-equilibrated and free of any reactive species, such as oxygen and water. Care must also be taken not to decompose a sample to be injected in the interval between sampling and injection. In general, it is advisable to check frequently the reproducibility and reliability of the glc analysis by calibration with standard mixtures and by repetitive injections.

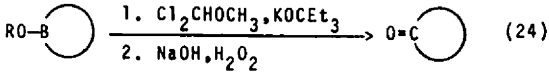
2. Carbonylation, carbenation (DCME) and cyanoboration

The carbonylation of trialkylboranes[16] has provided for the first time a means of converting trialkylboranes into the corresponding carbon compounds while retaining all of the original structural features of the organoboranes (e.g. eqns 15 and 19). Since the carbon compounds thus obtained are generally much more readily identified and characterized, the reaction provides a powerful tool for the identification of organoborane heterocycles. Although conversion of trialkylboranes into trialkylcarbinols usually requires heating the reaction mixtures to *ca.* 150°C, certain intermediate species, which evidently are far more stable thermally than the initial organoboranes, are formed at relatively low temperatures (≤ 50°C). Under these conditions, no extensive molecular rearrangements have been observed, although, in some extreme cases, where high temperatures are required for the uptake of carbon monoxide, the reaction has been accompanied by isomerization.[48] Cyanotrialkylborates, readily obtainable from trialkylboranes and sodium cyanide, react with acylating agents, such as trifluoroacetic anhydride, to form, after oxidation, ketones and trialkylcarbinols[49] (eqn 23).



Thus, the cyanoboration reaction may be used in place of carbonylation, although the scope of the former is not yet as well defined as that of the latter.

One major drawback associated with these reactions is that only trialkylboranes have been successfully utilized, various dialkylborane derivatives, such as B-methoxydialkylboranes, being either inert or not applicable. The difficulty, however, has been largely overcome by the development of the DCME reaction of organoboranes,[50] readily applicable even to B-alkoxydialkylboranes (eqn 24).



In our systematic studies, the following set of analytical methods has been routinely utilized in the examination of the hydroboration mixtures:

(a) Quantitative determination of residual hydride by analysis of the hydrogen produced by methanolysis or hydrolysis.

(b) Low temperature glc analysis and ^{1}H NMR examination of the methanolyzed reaction mixture.

(c) IR and ^{1}H NMR examination of the hydroboration mixture.

(d) Glc analysis of the oxidation products.

(e) Identification of isolated trialkylboranes and B-methoxydialkylboranes.

In addition to these, identification and characterization of the products of the carbonylation or DCME reaction have been performed, as needed.

All of these techniques are also applicable to establishing the structures of isolated organoboranes. In such cases, various additional techniques, including those described below, may also be applicable.

(a) ^{1}H NMR examination of "ate" complexes with

amines,[44] hydrides,[51] and so on, is often highly useful. The B decoupled ^1H NMR appears especially promising.[51] ^{13}C and ^{11}B NMR are also highly promising, but their usefulness in this area has not been well delineated.

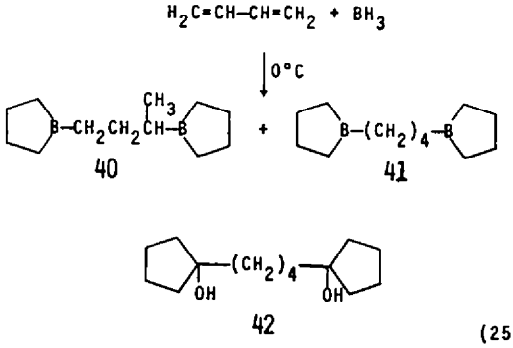
(b) Use of X-ray analysis in this area has been quite limited in the past. Complexation with appropriate bases should help produce stable crystals suitable for X-ray analysis.

B. Structures of the Products Obtained by the Hydroboration of Dienes and Polyenes with Borane–THF

1. 1,3-*Butadiene*

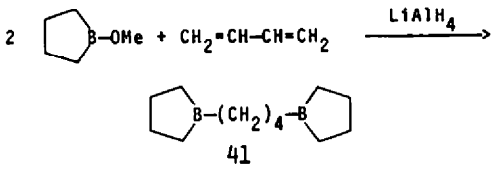
Prior to our systematic investigation of the hydroboration of 1,3-butadiene, several groups of workers had examined this reaction.[52] Unfortunately, some of these earlier studies led to results and conclusions that have since been shown to be either inaccurate or incorrect, as discussed below.

Hydroboration in the stoichiometric 3:2 *ratio-kinetic products.* The hydroboration of 1,3-butadiene with borane–THF in the 3:2 ratio at 0°C (eqn 25) produces predominantly the dumbbell-shaped organoboranes, 1,3- (**40**) and 1,4-bis(1-borolyl)butane (**41**), the ratio of the two observed under kinetically controlled conditions being *ca.* 70:30, as seen by low temperature glc (SE-30).[25a]



(25)

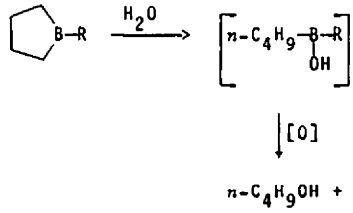
The structure of **41** was unequivocally established by (a) its conversion to **42** via carbonylation-oxidation[25a] formed as the only major product observed by glc in the expected region and (b) an independent synthesis by the procedure shown in eqn (26).[25a]



(26)

Evidently, the reactive bisborolane is produced *in situ* and hydroborates 1,3-butadiene in a highly regioselective manner. Although **40** has never been isolated as a pure substance, it has been adequately identified as follows. (a) Glc analysis of the oxidation products derived from a 70:30 mixture of **40** and **41** indicates that **40** is converted to a 1:2 mixture of 1,3- and 1,4-butanediols.[25a] (b) Hydrolysis of the same 70:30 mixture of **40** and **41** produces **43**, readily purified by distillation through a spinning band column (bp 70° at 1 mm), which on oxidation, produces a 1:2 mixture of 1,3-butanediol and 1-butanol.[25a] We depict the course of the reaction as below (eqn 27).

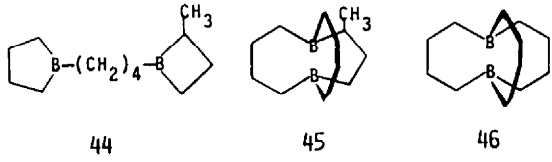
In this study, we have found that, although the C–B bond is usually quite stable to water, the borolane ring is highly susceptible to hydrolysis.[25a]



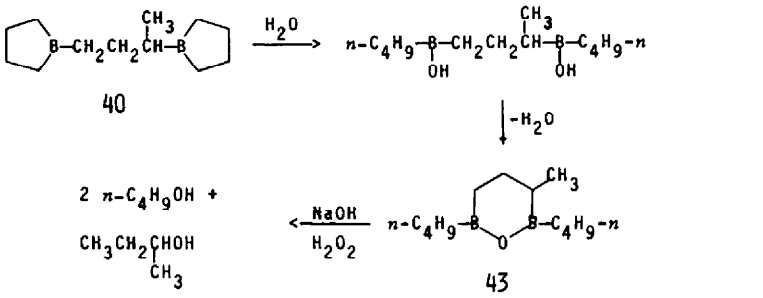
(28)

Evidently, **41** is also converted to the corresponding diol, which, unlike the one in eqn (27), does not readily cyclize, thereby allowing an easy isolation of **43**. In any case, the results strongly favor the structure **40** over the only other alternative structures, **44** and **45**. In no case has there been any indication for the formation of **44–46**.

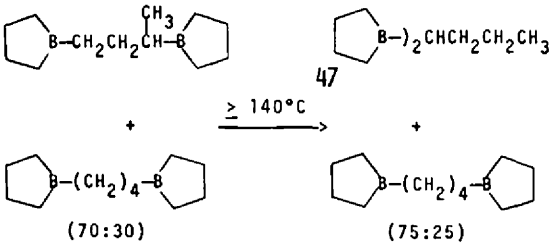
Thermal products. A highly unusual isomerization reaction was observed when the initial 70:30 mixture of **40** and **41** was heated to ≥140°C.[25a] In brief, **40** disappeared within a few hours at 170°C. The amount of **41** increased initially, but then gradually decreased. The product, after 12 hr, consisted of a 25:75 mixture of **41** and a new product, **47**, which had a slightly shorter glc retention time than **40**. No mention of its formation had ever been made in any previous studies.



Oxidation of a pure sample of **47** (b.p. 64–65° at 1 mm) by alkaline hydrogen peroxide produced a 1:2 mixture of 1-butanol and 1,4-butanediol. Methanolysis of **47** produced a 1:1 mixture of B-methoxy-borolane and B-(*n*-butyl)borolane. Finally, the structure **47** was con-



(27)



(29)

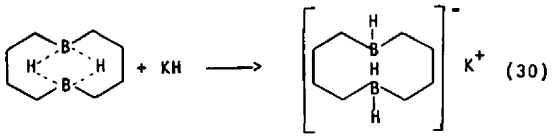
firmed by an independent synthesis by the reaction of B-methoxy-borolane with lithium aluminum hydride in the presence of 1-butyne.[25a]

A more recent ^{1}H NMR study by Shore[51] of the "ate" complex derived from **47** and a metal hydride further corroborates our original structural assignment.

Hydroboration in a 1:1 *ratio.* The hydroboration of 1,3-butadiene with borane–THF in a 1:1 molar ratio produces a polymeric material.[24] The remaining B–H bonds exhibit more or less the usual reactivity of such bonds and undergo rapid hydrolysis and methanolysis at 0°C. However, distillation of the 1:1 polymeric product produces in high yield (~70%) a 1:1 dimer of unusual stability. Thus, the compound does not react either with water or with olefins at appreciable rates below 100°C. The originally proposed structure **48**[52a] appeared incompatible with these unusual properties. We therefore proposed the alternate structure, **49**.[23]

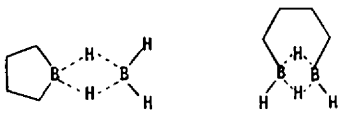
48 **49**

The highly unusual characteristics of the compound are readily understood in terms of the 1,6-diboracycloododecane structure (**49**), where the *trans*-annular bridge could greatly stabilize the usually reactive boron–hydrogen structure and render this moiety highly inert toward reagents which usually attack it with ease. Our subsequent study[53] permitted us to conclude that **49** was indeed the structure of the 1:1 stable dimer. In addition to the mass spectral data which indicated the presence of a dimeric species (*m/e* 136) but not of a monomer (*m/e* 68), protonolysis of the 1:1 stable dimer formed 1,4-butanediboronic acid. Clearly, these results are compatible with **49**, but not with **48**. This conclusion was further confirmed by Shore by the molecular weight determination of amine complexes of the stable dimer[54] as well as by ^{1}H NMR examination of the "ate" complex formed by the reaction of the dimer with potassium hydride.[51]



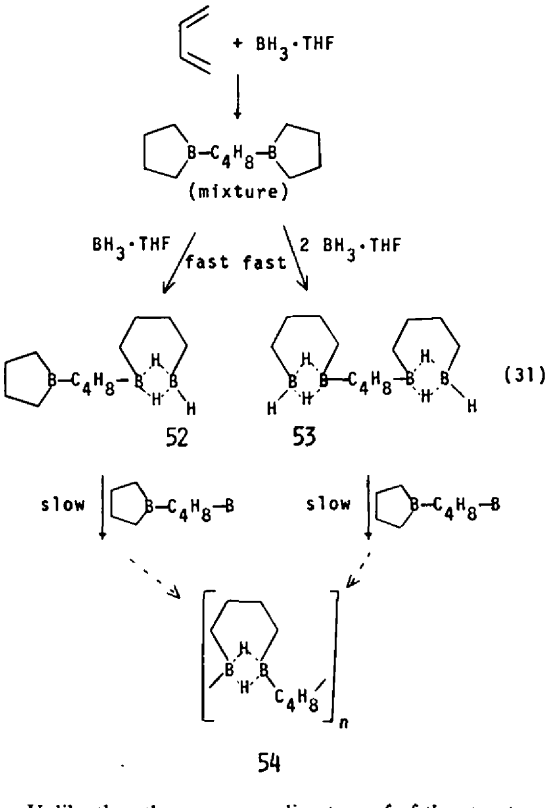
(30)

Similarly, Köster's assignment[11] of **50** to a material obtained from **49** and diborane has been questioned by Shore,[54] who believes that Köster prepared **51** rather than **50** on the basis of the IR spectrum of the compound.



50 **51**

The structure of the initial polymeric 1:1 product is less clear. However, our extensive investigation[25b] permits the following tentative formulation (eqn 31).

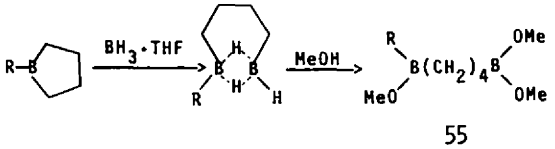


(31)

52 **53** **54**

Unlike the other cases, no direct proof of the structure exists. However, the scheme shown in eqn (31) appears strongly supported by the following observations.

First, 1:1 hydroboration by the addition of borane–THF to 1,3-butadiene proceeds largely through the formation of the 3:2 products **40** and **41**. Thus, when only two-thirds of the borane–THF is added, glc examination of the mixture indicates the presence of the 3:2 products in high yields which, on further addition of borane–THF, disappear rapidly.[25b] This led us ot study the reaction of simple B-alkylborolanes with borane–THF. Indeed, this study has revealed that B-alkylborolanes react rapidly with borane–THF to form intermediates which, on methanolysis, produces **55** in excellent yields[25b,55] (eqn 32).



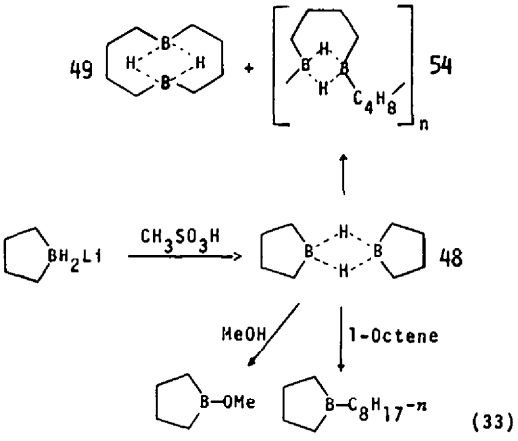
55

(32)

Second, when an isolated 70:30 mixture of the dumbbell 3:2 products is mixed with two equivalents of borane–THF, both of these reactants disappear com-

pletely within 15 min at room temperature. The product has not been isolated, but its IR spectrum (2510 cm^{-1} for the terminal B–H, 1570 cm^{-1} for the B–H–B bond, absence of the 2400 cm^{-1} band for BH_3·THF) and absence of bisborolane (**48**), 1,2-tetramethylenediborane (**51**), the stable 1:1 dimer (**49**), or the 3:2 compounds (**40** and **41**) evidenced by glc examination after methanolysis strongly indicate that the product must be **53**.[25b] When this product **53** is treated with an equimolar amount of the 3:2 product (**40** and **41**), a rather slow reaction, which is accompanied by the disappearance of the IR band at 2510 cm^{-1} for the terminal B–H bond as well as of the 3:2 compound (glc), takes place over *ca.* 24 hr at room temperature.[25b] The product is indistinguishable in all respects from the 1:1 polymeric product **54**.

Finally, the highly elusive bisborlane (**48**) has been prepared according to eqn (33) and has been shown to be highly unstable and highly reactive toward methanol and olefins.[56]

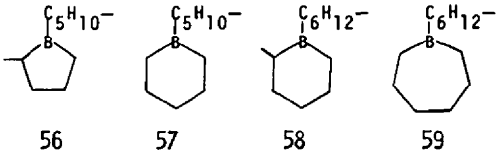


(33)

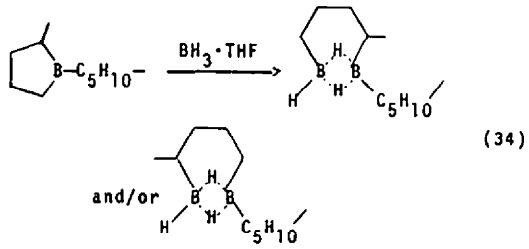
2. *1,4-Pentadienes and 1,5-hexadienes*

The success we had observed in the study of the hydroboration of 1,3-butadiene prompted us to apply the same methodology and techniques to other cases. The limited amount of space does not permit detailed discussions. A brief summary of the results obtained in a manner similar to that described above will therefore be presented.

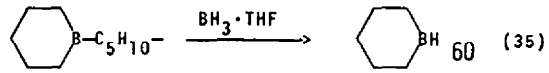
As with 1,3-butadiene, the hydroboration of 1,4-pentadiene[31] and 1,5-hexadiene[34] with borane–THF in the 3:2 ratio evidently produces in high yields (70–80%) the corresponding dumbbell products containing the structural moieties **56–59**.



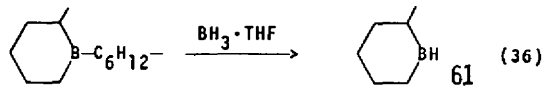
The 1:1 kinetic product derived from 1,4-pentadiene is *ca.* 70% polymeric and only *ca.* 30% cyclic. The cyclic product is mostly borinane (**60**) along with a minor amount of 2-methylborolane. On the other hand, the 1:1 kinetic product derived from 1,5-hexadiene is 78% cyclic, and is a 70:30 mixture of borepane (**62**) and 2-methylborinane (**61**). At least in cases where borane–THF is added to these dienes, the 1:1 products appear to form largely via the 3:2 products, as in the case of 1,3-butadiene. We depict the formation of the 1:1 products as follows (eqns 34–37).



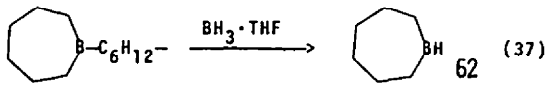
(34)



(35)

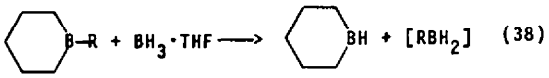


(36)

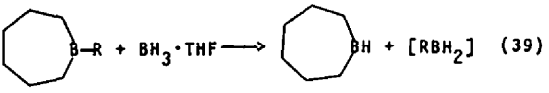


(37)

In marked contrast to the reaction of B-alkylborolanes with borane–THF (eqn 32), the reaction of b-alkylborinanes and B-alkylborepanes with borane–THF does not involve an opening of these boracyclane rings. Instead, the alkyl–boron bond is selectively cleaved, forming the corresponding boracyclanes (**60** and **62**) and monoalkylboranes, the latter of which tend to undergo further disproportionation[55] (eqn 38 and 39).

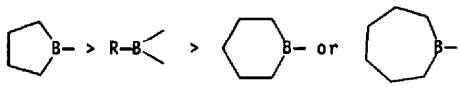


(38)



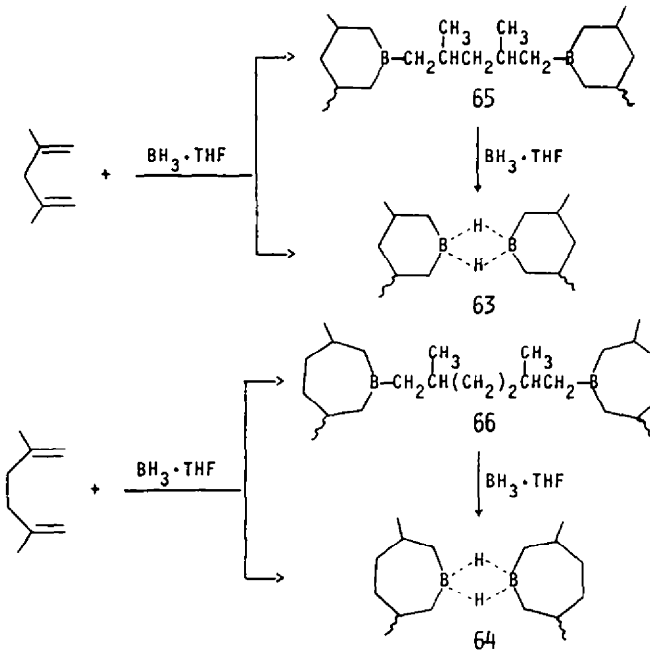
(39)

Thus, the order of reactivity of various B–C bonds toward borane–THF may be summarized as follows:



Clearly, the interpretations presented in eqns (34)–(37) are consistent with this generalization.

Placement of two Me groups at the two internal olefinic carbons of 1,4-pentadiene or 1,5-hexadiene greatly simplifies the course of the hydroboration. Thus, the hydroboration of 2,4-dimethyl-1,4-pentadiene and 2,5-dimethyl-1,5-hexadiene with borane–THF in a 1:1 ratio at 0° produces after several hours bis(3,5-dimethyl)borinane (**63**) and bis(3,6-dimethyl)borepane (**64**) in *ca.* 90 and 75% yields, respectively.[39] However, the amounts of these bisboracyclanes observed immediately following completion of the hydroboration are considerably less. Moreover, IR examination indicates the presence of an appreciable amount of borane–THF (2400 cm^{-1}). Therefore, **63** and **64** must be formed at least in part via the corresponding 3:2 compounds **65** and **66**, as in other cases (eqns 40 and 41).



(40)

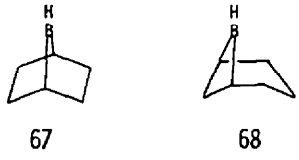
(41)

3. *Higher α,ω-dienes*

The hydroboration of 1,7-octadiene with borane–THF in a 1:1 ratio yields a gelatinous material which is insoluble in ethereal solvents such as THF. Essentially no cyclic product is formed.[33a]

4. *Cyclic and "mixed" dienes*

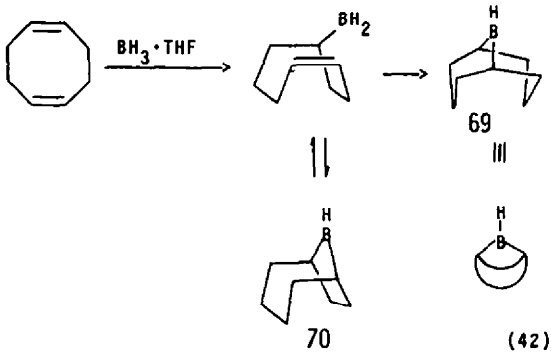
The hydroboration of 1,4-cyclohexadiene with an equimolar amount of borane–THF does not produce the expected boracyclanes **67** and **68**.[25c]



67 68

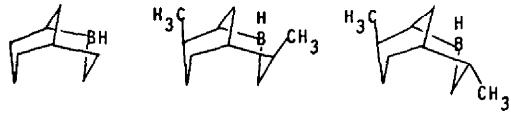
Except for the regiochemistry and stereochemistry presented in the previous section (Section II), little is known about the exact course of the reaction.

On the other hand, the 1:1 hydroboration of 1,5-cyclooctadiene with borane–THF yields a 72:28 mixture of 9-borabicyclo[3.3.1]nonane (9-BBN) (**69**) and its [4.2.1] isomer (**70**).[40] The latter can be readily isomerized to 9-BBN at 65°C. The overall sequence provides 9-BBN in nearly quantitative yield (eqn 42).



(42)

Somewhat unexpectedly, the 1:1 hydroboration of 4-vinylcyclohexene (**25**) and limonene (**26**) with borane–THF yields mixtures of bicyclic organoboranes only in low yeilds (12 and 25%, respectively).[33a] Thermal treatment of the products does not markedly increase the amounts of the cyclic organoboranes. However, on distillation of the methanolyzed hydroboration product derived from 4-vinylcyclohexene, a mixture of B-methoxyboracyclanes was obtained in 56% overall yield.[33a] Glc examination of the oxidation products derived from the distillate indicates that the OMe derivative of **71** accounts for 64% of the mixture.



71 72 73

Similarly, distillation of the methanolyzed 1:1 hydroboration mixture derived from limonene produces a 1:1 mixture of the methoxy derivatives of **72** and **73** in 74% yield.

5. *Summary of the cyclic hydroboration of dienes with borane–THF*

The amounts of cyclic organoboranes observed in the 1:1 hydroboration of various dienes with borane–THF are summarized in Table 2.[25b] Based on these results, we may tentatively conclude that the hydroboration of dienes capable of producing common rings (5- through 7-membered) is often highly cyclic. The rapid hydroboration reaction is accompanied by the alkyl-hydrogen exchange reaction. Thus, in many cases, the fully alkylated 3:2 compounds are the major initial products, irrespective of the reactant ratio. The formation of higher polymers in the case of 1,3-butadiene and 1,4-pentadiene is largely a result of the remarkably facile opening of the borolane ring sysem. On the other hand, the reaction products from longer chain α,ω-dienes appear genuinely polymeric.

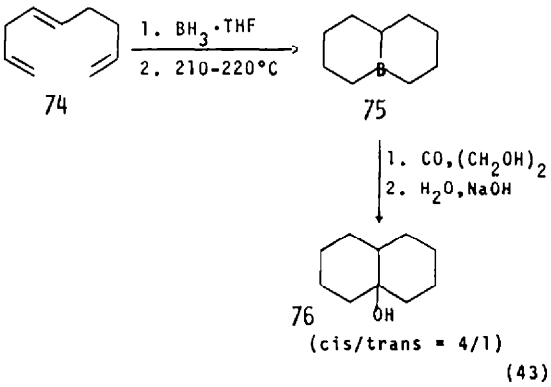
Table 2. Cyclic hydroboration of dienes with borane–THF in a 1:1 ratio (1–24 hr at 0°C)

Diene	Total boracyclane, %	Product distribution, %
1,3-Butadiene	0	
1,4-Pentadiene	30	Borinane (83) 2-Methylborolane (17)
1,5-Hexadiene	78	Borepane (70) 2-Methylborinane (30)
2,4-Dimethyl-1,4-pentadiene	89	3,5-Dimethylborinane (99) Unidentified by-product (trace)
2,5-Dimethyl-1,5-hexadiene	75	3,6-Dimethylborepane (91) Unidentified by-product (9)
1,7-Octadiene	0	
1,4-Cyclohexadiene	0	
1,5-Cyclooctadiene	91	9-Borabicyclo[3.3.1]nonane (72) 9-Borabicyclo[4.2.1]nonane (28)
4-Vinylcyclohexene	12	At least 3 products
D-(+)-Limonene	25	At least 4 products

6. *Polyenes*

The structures of the organoborane heterocycles derived from 1,5,9-cyclododecatriene have already been discussed in detail (Section II). Only a few acyclic trienes appear to have been subjected to the reaction with borane complexes.

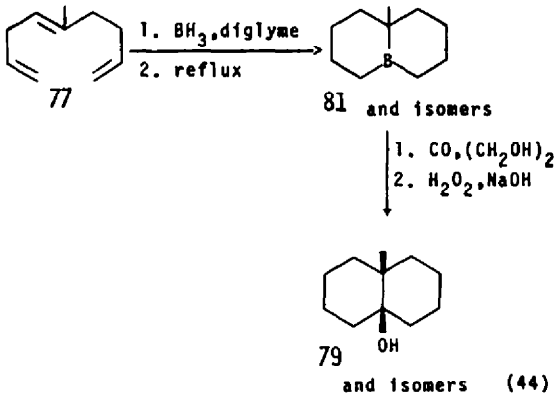
Hydroboration of 1,4,8-nonatriene (**74**) with borane–THF at 0°C in a 1:1 ratio produces an insoluble material, apparently polymeric boranes. Depolymerization at 210–220° (3 hr) followed by distillation gives 9-boradecalin (**75**), b.p. 100–105° (100 mm), in 41% yield.[57] The carbonylation-oxidation of **75** provides a 4:1 mixture of *cis* and *trans*-9-decalols (**76**) in 89% yield (eqn 43).[57]



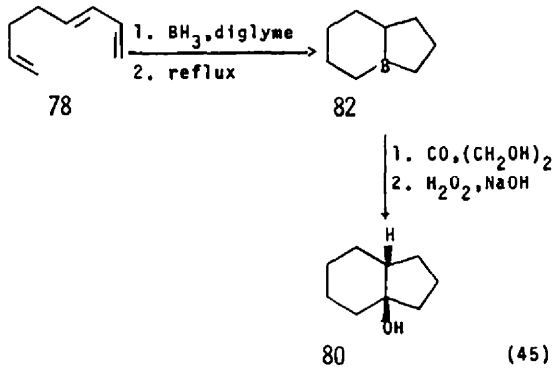
(43)

Our subsequent study indicates that the organoborane product obtained by the hydroboration of **74** with borane–triethylamine at 130–140°C is a rather complex mixture of several isomers which, on further thermal treatment, can be converted to a relatively pure sample of **75** in 70–80% yield.[58]

Although no detailed study of the structure of organoboranes has been made, similar results have been obtained with trienes **77** and **78**. The bicyclic alcohols **79** and **80** have been obtained in 46% and 33% yields, respectively.[58] The intermediate organoboranes must be **81** and **82**, respectively (eqns 44 and 45).



(44)



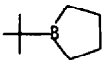
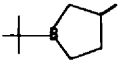
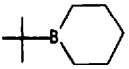
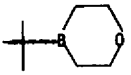
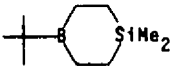
(45)

As in the cases of perhydro-9b-boraphenalenes (Section III), the carbonylation-oxidation of **75**, **81** and **82** is highly stereoselective. Unfortunately, however, no satisfactory explanation exists at present.

C. Structures of the Products from Hydroboration of Dienes with Mono-substituted Boranes

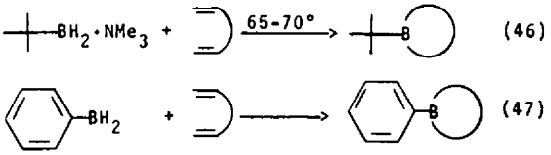
In 1960, Hawthorne[28] and Mikhailov[27] prepared several organoborane heterocycles by the hydroboration of

Table 3. B-*tert*-Butylboracyclanes via cyclic hydroboration of dienes with *tert*-butylborane–trimethylamine at 65–70°C

Diene	*B-tert*-Butyl-boracyclanes	Yield %	Bp °C(mm Hg)
1,3-Butadiene		60	55(55)
Isoprene		55	67(54)
1,4-Pentadiene		38[a]	44(12)
Divinyl ether		70	90(56)
Divinyldimethylsilane		58	44(2)

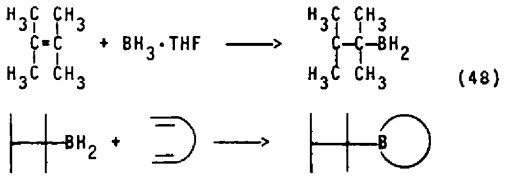
[a]Based on the results obtained with thexylborane, it is probable that *B-tert*-butyl-2-methylborolane was also formed.

dienes with *tert* - butylborane - trimethylamine and phenylborane, respectively (eqns 46 and 47). The results obtained with *tert* - butylborane - trimethylamine are summarized in Table 3.

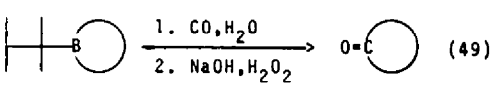


1. *Cyclic hydroboration with thexylborane*

To circumvent the inconvenience associated with the preparation of *tert* - butylborane - trimethylamine, we considered the use of a readily available monoalkylborane, 1,1,2-trimethylpropylborane (thexylborane)[59] which in conveniently prepared by the hydroboration of 2,3-dimethyl-2-butene with one equivalent of borane–THF, and undertook a study of its reaction with a representative series of dienes (eqn 48).[33b]

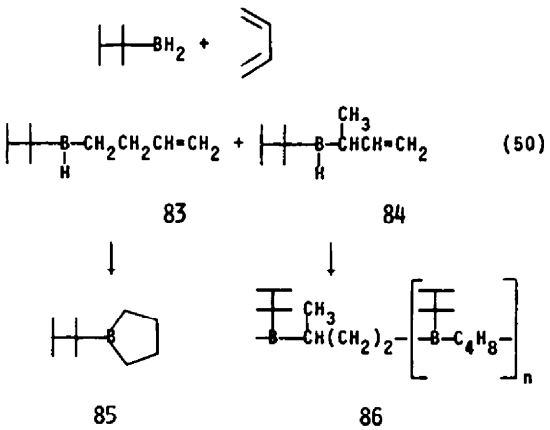


This study was prompted by our finding that the thexyl group effectively acts as a blocking group in the conversion of B-thexylboracyclanes into the corresponding cyclic ketones via carbonylation-oxidation (eqn 49).[60]



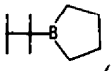
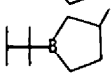
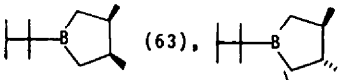
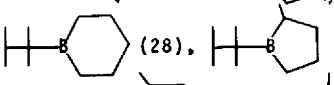
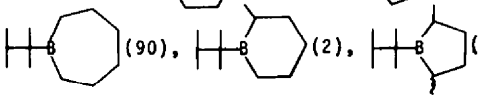
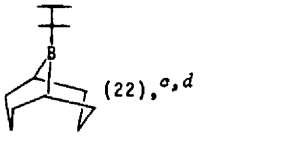
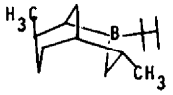
The results summarized in Table 4 indicate the following. First, the hydroboration of dienes capable of forming common rings with thexylborane in a 1:1 ratio followed by distillation readily produces the corresponding B-thexylboracyclanes in high yields in the great majority of cases we have so far studied.[33b] Although no detailed study has been made, a preliminary study indicates that 1,4-cyclohexadiene and 1,7-octadiene do not appear to form organoborane heterocycles in any appreciable amounts in the reaction with thexylborane.

Second, the contrasting behavior observed with 1,3-butadiene and 2,3-dimethyl-1,3-butadiene is noteworthy. The hydroboration of 2,3-dimethyl-1,3-butadiene with thexylborane must involve a simple cyclization reaction. On the other hand, the product from 1,3-butadiene is ~80% polymeric. The initial products of the 1,3 - butadiene - thexylborane reaction must be a mixture of **83** and **84**. Each of these has a considerably more reactive double bond than the parent 1,3-butadiene and therefore must react preferentially. Since there has been no indication for the formation of 4-membered organoboranes via hydroboration, it is reasonable to assume that **83** is selectively transformed into **85**. Polymerization does not appear competitive in such a case. On the other hand, if **84** would not cyclize to form the corresponding 4-membered organoborane, it would then trigger a polymerization reaction to form **86** (eqn 50).



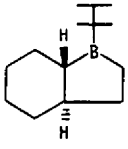
Third, the preferential formation under the kinetically controlled conditions of 5-membered rings over 6-mem-

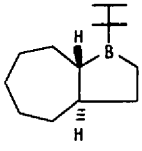
Table 4. B-Thexylboracyclanes via the cyclic hydroboration of dienes with thexylborane in THF at 0°C

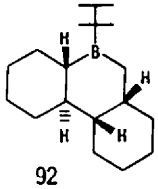
Diene	Combined yield of B-Thexylboracyclanes, % Glc[a]	Distillation	Isomer distribution of distillate, (%)[b]	Bp, °C(mm)
1,3-Butadiene	17	71	 (100)	72(19)
Isoprene	—	54	 (100)	55(4)
2,3-Dimethyl-1,3-butadiene	93	89	 (63), (37)	72-74(4)
1,4-Pentadiene	81	83	 (28), (72)	57-58(4)
1,5-Hexadiene	85	82	 (90), (2), (8)	79-80(4)
1,5-Cyclooctadiene	—	91	 (22),[c,d]  (78)[c,d]	93-94(0.4)
Limonene	—	72	 (100)[c,e]	88(0.4)

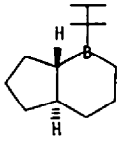
[a] On a 2-ft SE-30 column (Chromosorb W). [b] The isomer distributions before and after distillation by glc analysis of B-thexylboracyclanes were essentially the same except in the cases of isoprene, 1,5-cyclooctadiene, and D-(+)-limonene where no glc analysis of B-thexylboracyclanes was performed. [c] Isomer distribution based on glc analysis of the oxidation products. [d] Isomer distribution before distillation (1,5-/1,4- = 22/78). [e] Epimer ratio not determined.

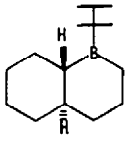
bered rings observed with borane–THF is also observed with thexylborane. Finally, although not listed in Table 4, the following B-thexylboracyclanes (**87–92**) must have been formed from the corresponding dienes in a completely stereoselective manner, as discussed earlier (Section II).

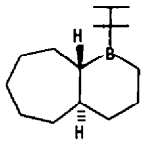

87


88


92


89


90

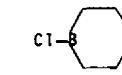
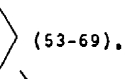
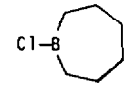
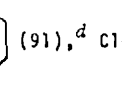
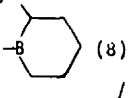
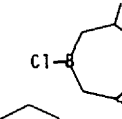
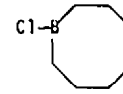
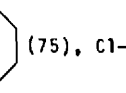
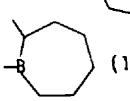

91

2. Cyclic hydroboration with monochloroborane-ethyl ether

Recently, monochloroborane-ethyl ether has become readily available.[20] It shows high regioselectivity in its hydroboration reaction with various olefins.[20] The hydroboration products, B-chlorodialkylboranes, can readily be methanolyzed to the corresponding B-methoxydialkylboranes that are not only suitable for glc examination but can serve as useful intermediates for organic synthesis. All of these considerations prompted us to make a systematic study of its reaction with a representative series of dienes.[32] Prior to our study, Mikhailov *et al.*[29] investigated the reaction of monochloroborane-ethyl ether with 1,3-butadiene, 1,4-pentadiene and 1,5-hexadiene. The results of our study, as well as those obtained by the Mikhailov group, are summarized in Table 5. The diol distributions are summarized in Table 1.

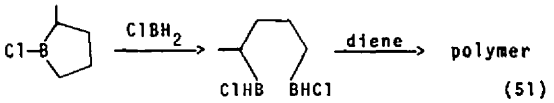
The results summarized in Table 5 indicate the following. First, as with thexylborane, the hydroboration of dienes with monochloroborane-ethyl ether, followed by thermal treatment-distillation, provides B-chloroboracyclanes in high yields except in the case of 1,3-butadiene. Second, in marked contrast to the reaction of thexylborane, the reaction of dienes with monochloroborane gives predominantly polymeric products, even when the dienes are capable of forming directly common rings.[32] Although this still remains an unsolved puzzle, the following reasonable interpretation may be presented at this point. Monochloroborane-ethyl ether is a highly regioselective reagent that hydroborates terminal olefins to place 99.5% of the boron at the terminal position.[20] If its reaction with α,ω-dienes were to involve straightforward polymerization via statistical hydroboration, the diols

Table 5. Cyclic hydroboration of dienes with monochloroborane-ethyl ether at 0°C

Diene	Combined yield of B-Chloroboracyclanes,[a] % Glc	Distillation	Isomer distribution of distillate,[b] %	Bp, °C(mm)
1,3-Butadiene	—	40[c]	(100)	—
1,4-Pentadiene	31	89	 (53-69),  (31-47)	45-58(80)
1,5-Hexadiene	24	93	 (91),[d]  (8),[d]  (1)[d]	56-58(30)
2,5-Dimethyl-1,5-hexadiene	—	87		70-72(15)
1,6-Heptadiene	3	91	 (75),  (10),  (15)	66-68(18)
1,7-Octadiene	0	77	1,8-(1), 1,7-(3), 1,6-(12), 1,5-(66), 1,4-(6), 2,6-(8), and 2,5-(4)	68-70(10)

[a] By glc analysis of the methanolysis products. [b] By glc analysis of the oxidation products. [c] Isolated as the B-butoxy derivative. [d] A considerably different ratio of 74:16:10 was observed by Mikhailov, et al.[29]

obtained after oxidation must contain the α,ω-diol to the extent of 99%. Based on the diol distributions, summarized in Table 1, the hydroboration of 1,6-heptadiene and 1,7-octadiene with monochloroborane follows the above prediction very closely. We tentatively conclude that these reactions involve simple polymerization. On the other hand, the diol distributions observed with 1,4-pentadiene and 1,5-hexadiene are clearly anomalous. Interestingly, the distributions observed in the initial polymeric products and in the distillate are nearly the same. We can only conclude that these reactions must be cyclic to a considerable extent and that the cyclic products undergo change under the hydroboration conditions. We have previously observed that the borolane ring is sensitive to rupture by borane-THF.[55] Possibly a similar reaction occurs with monochloroborane-ethyl ether, as indicated in eqn (51).



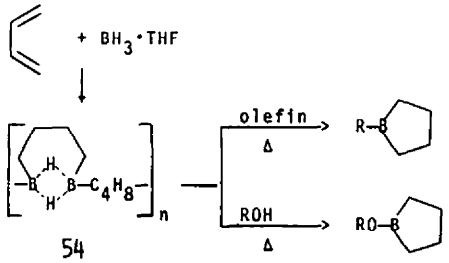
(51)

IV. SYNTHESIS OF BISBORACYCLANES, B-METHOXYBORACYCLANES AND B-ALKYLBORACYCLANES

We now understand reasonably well both the structures and the quantities of products produced in the hydroboration of dienes and polyenes, as well as the mechanistic pathways involved in these reactions. We must now move a step ahead and learn how to synthesize organoborane heterocycles of synthetic interest. In fact, in many favorable cases, we have already established satisfactory procedures for their syntheses. This section summarizes these and additional results obtained within the past several years.

1. *Bisborolane, B-methoxyborolane and B-alkylborolanes*

The synthesis of the highly elusive bisborolane[56] has already been discussed (eqn 33) (Section III.B.1). Because of its exceptional instability, it does not serve as a convenient precursor to the B-alkylborolanes and B-alkoxyborolanes. Fortunately, the polymeric 1:1 product (**54**) of the 1,3-butadiene-borane reaction serves as a convenient intermediate for both B-alkylborolanes and B-alkoxyborolanes[27b] (Method I) (eqn 52).



(52)

Hydroboration of olefins with **54** is considerably slower than in the case of ordinary dialkylboranes, presumably due to the pseudocyclic structure present in **54**.[27b] The yields of B-alkylborolanes are in the range of 55–65%, due mainly to the fact that only *ca.* 70% of 1,3-butadiene is converted into the tetramethylene unit required for the formation of the borolane ring. The results of the B-alkylborolane synthesis are summarized in Table 6.

Treatment of **54** with methanol provides B-methoxyborolane in good yield. B-Methoxyborolane reacts with lithium aluminum hydride in the presence of one equivalent of olefins to form the corresponding B-alkylborolanes[61] (Method II) (eqn 53).

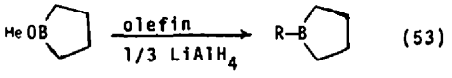
Table 6. Synthesis of B-alkylboracyclanes[a]

B-Alkylboracyclanes	Method[b]	Yield,[c] %	Bp, °C(mm)	Reference
B-(*n*-Butyl)borolane	I	63	62-65(50)	28b
	II	56	52-54(20)	61
B-(*n*-Pentyl)borolane	I	56	65-68(12)	28b
B-(*n*-Octyl)borolane	I	53	104-105(5)	28b
	II	—(90)	——	61
B-Cyclopentylborolane	I	58	87-88(30)	28b
	II	60	77-78(20)	61
B-Cyclohexylborolane	I	57	96-97(20)	28b
B-(*n*-Butyl)borinane	III	79(90)	78-81(18)	31,62
B-(*n*-Pentyl)borinane	II	67(89)	92-95(20)	61
	III	81(93)	——	31,62
B-(*n*-Octyl)borinane	II	—(92)	——	61
B-(*sec*-Butyl)borinane	III	73(88)	64-67(20)	31,62
B-Cyclopentylborinane	III	75(91)	97-100(19)	31,62
B-Cyclohexylborinane	II	75(90)	112-115(18)	61
	III	90(93)	115-118(20)	31,62
B-(*exo*-Norbornyl)-borinane	II	74(88)	128-130(20)	61
	III	76(91)	——	31,62
B-(*n*-Hexyl)-3,5-DMBN[d]	III	90(95)	122-124(17)	39
B-Cyclopentyl-3,5-DMBN	III	84(93)	112-114(17)	39
B-(*tert*-Butyl)-3,5-DMBN	IV	88(98)	72-73(11)	39
B-(*n*-Hexyl)-3,6-DMBP[d,e]	III	89(97)	108-112(3)	39
B-Cyclopentyl-3,6-DMBP	III	91(98)	96-100(3)	39
B-Methyl-9-BBN[f]	IV	—(94)	23-24(0.5)	63
B-Ethyl-9-BBN	IV	—(93)	32-34(0.2)	63
B-Isopropyl-9-BBN	IV	88(90)	35.5-37(0.25)	63
B-(*n*-Butyl)-9-BBN	IV	—(89)	58-59(0.5)	63
B-Isobutyl-9-BBN	IV	85	120-126(15)	89
B-(*sec*-Butyl)-9-BBN	IV	—(94)	56-58(0.2)	89
B-(*tert*-Butyl)-9-BBN	IV	82(90)	27-28(0.02)	63
B-Neopentyl-9-BBN	IV	86(97)	68-69(0.7)	63
B-Cyclopropyl-9-BBN	V	70	64-65(15)	77a
B-Cyclobutyl-9-BBN	V	71	113(10)	77b
B-Cyclopentyl-9-BBN	IV	84	68-70(0.2)	63
B-(*trans*-2-Methyl-cyclopentyl)-9-BBN	III	88	75-76(0.1)	89
B-Cyclohexyl-9-BBN	III	—	87-96(0.2)	89
B-(2-Cyclohexenyl)-9-BBN	III	71	84-87(0.03)	90
B-(3-Cyclohexenyl)-9-BBN	III	85	72-76(0.03)	91
B-(4-Cyclooctenyl)-9-BBN	III	85	105-110(0.03)	91
B-(*endo*-5-Norbornenyl)-9-BBN	III	31	88-92(0.03)	91

Table 6. (*Contd.*)

B-Alkylboracyclanes	Method[b]	Yield,[c] %	Bp, °C(mm)	Reference
B-Phenyl-9-BBN	IV	—(100)	90(0.4)	63
B-(*p*-Tolyl)-9-BBN	VI	85	155-160(5.5)	92
B-Benzyl-9-BBN	IV	85(97)	105-125(0.5)	63
B-Allyl-9-BBN	IV	83(95)	41-42(0.05)	63
B-Crotonyl-9-BBN	IV	98	55-56(0.05)	90
B-(2-Methallyl)-9-BBN	IV	84	55-56(0.04)	90
B-Isoprenyl-9-BBN	III	87	54-56(0.01)	90
B-[2-(4'-Cyclohexenyl)-ethyl]-9-BBN	III	93	103(0.035)	89
B-(4-Octynyl)-9-BBN	III	85	100-104(0.06)	66

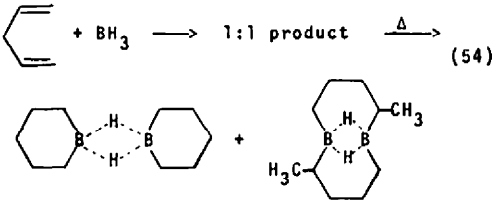
[a]Only those *B*-alkylboracyclanes which have been isolated and characterized are listed. A number of other *B*-alkylboracyclanes have been prepared *in situ* and utilized in subsequent reactions. [b]I = Hydroboration of 1,3-butadiene with borane-THF in a 1:1 ratio followed by addition of an olefin and distillation (eq 52, ref 25b). II = Reaction of a *B*-methoxyboracyclane with lithium aluminum hydride or other metal hydrides in the presence of an olefin (ref 61). III = Hydroboration of an olefin with a bisboracyclane. IV = Reaction of a *B*-methoxyboracyclane with alkyl metals (ref 63). V = See ref 77. VI = Reaction of 9-BBN with an organolithium followed by treatment with methanesulfonic acid (ref 92). [c]By isolation. The numbers in parentheses are glc yields. [d]DMBN = dimethylborinane. [e]DMBP = dimethylborepane. [f]BBN = borabicyclo[3.3.1]nonane.



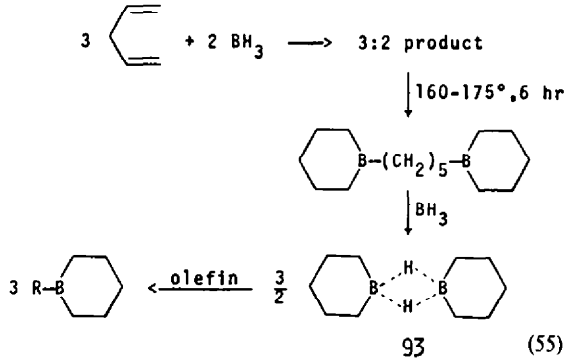
(53)

2. *Bisborinanes, bisborepanes and their* B-*alkyl and* B-*alkoxy derivatives*

The hydroboration of 1,4-pentadiene with borane-THF, followed by thermal treatment and distillation, provides an approximately 50:50 mixture of bisborinane (**93**) and 2,7 - dimethyl - 1,6 - diboracyclodecane (**94**) in 90% yield [31] (eqn 54).

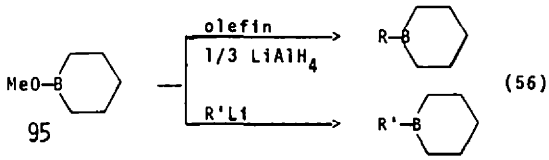


This mixture serves as a convenient reagent for the preparation of B-alkylborinanes and B-alkoxyborinanes, since **94** is inert to olefins and alcohols at room temperature. However, the loss of 1,4-pentadiene through the formation of **94** can be avoided in the following procedure (eqn 55).[31,62]



Although bisborinane can be obtained as a crystalline product, m.p. 52–54°; IR 1560 cm^{-1}, its isolation is usually not necessary. Its reaction with olefins at 0–25°C provides a convenient method for the synthesis of B-alkylborinanes (Method III).[31,62]

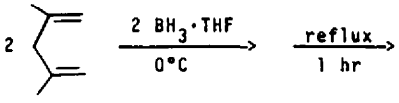
Treatment of **93** with methanol produces B-methoxyborinane in quantitative yield (97%). B-Methoxyborinane (**95**) can in turn be converted to B-alkylborinanes by its reaction with lithium aluminum hydride in the presence of olefins (Method II) (eqn 56).[61] In cases where the B-alkyl groups cannot be derived from olefins, B-methoxyborinane may be treated with alkyllithiums or Grignard reagents (Method IV) (eqn 56).[63]

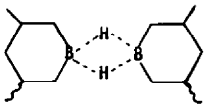


(56)

Generally speaking, once bisboracyclanes are obtained as thermally stable and pure compounds, they may be utilized as hydroborating agents (Method III) or converted into the B-methoxy or other alkoxy derivatives by alcoholysis, which may in turn be reacted with alkyllithiums or Grignard reagents (Method IV). These two routes appear to represent the most convenient methods available to use at present.

Bis(3,5-dimethyl)borinane (**63**) can be prepared as an insoluble compound, b.p. 79–82°C (1 mm); IR 1565 cm^{-1}, in 89% yield (94% by glc) by modifying slightly the hydroboration reaction discussed earlier (Section IV.B.2) (eqn 57).[39] The parent dialkylborane **63** has been converted to various B-alkyl and B-alkoxy derivatives, as shown in eqn (58). The results are summarized in Tables 6 and 7.

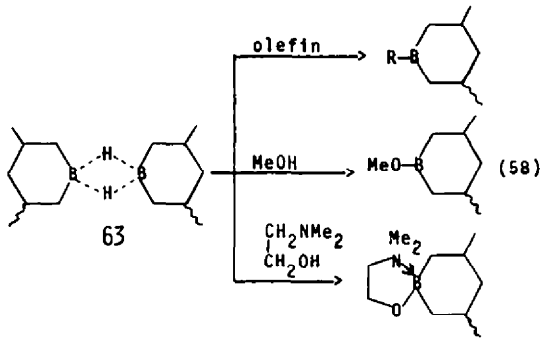




(57)

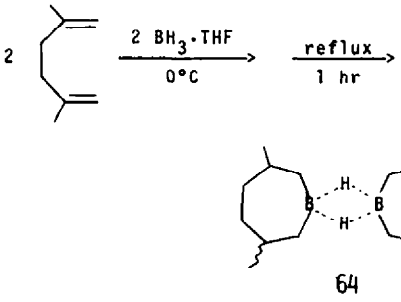
63

The same methods are applicable to the synthesis of bis(3,6-dimethyl)borepane (**64**) and its derivatives (eqn 59 and 60). The yield of **64** is ~75% and the product



(58)

contains ~6% of other isomers. Attempts to isolate **64** as a pure substance have not been successful.



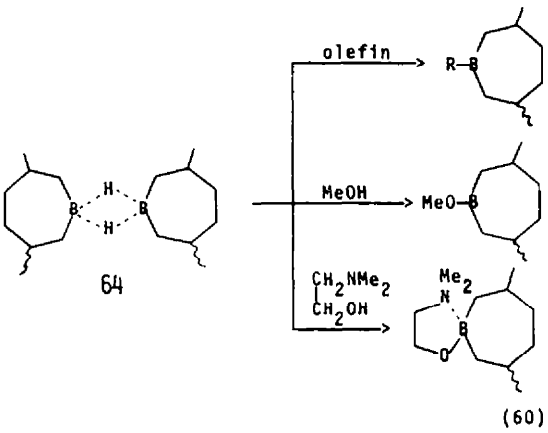
(59)

Bisborepane (**96**) has so far been obtained only as a mixture containing either 2-methylborinane (**61**), its dimer, and/or the mixed dimer with borepane (**62**), or 9-BBN (**69**) (its dimer).[34] The latter mixture was prepared as shown in eqn (61). The product is essentially free of **61**. More interestingly, this experiment clearly establishes that the central linear moiety of the dumbbell compound forms a cyclic product (**62**) on treatment with borane–THF.

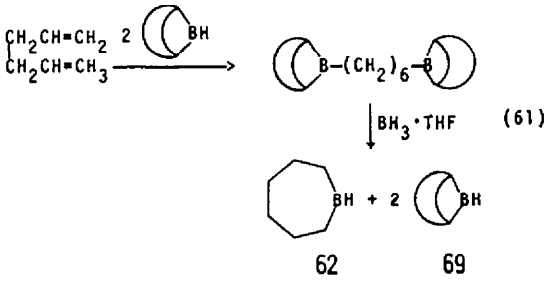
Table 7. Synthesis of B-alkoxyboracyclanes[a]

B-Alkoxyboracyclane	Yield,[b] %	Bp, °C(mm)	Reference
B-Methoxyborolane	70	44-46(90)	25a
B-Butoxyborolane	38	27-35(1)	29
B-Methoxyborinane	85	59-60(18)	31,62
B-Methoxy-3,5-dimethylborinane	84	74-76(32)	39
B-(β-Dimethylaminoethoxy)-3,5-dimethylborinane	83	110(3)	39
B-Methoxyborepane	84	74-76(32)	34
B-Methoxy-3,6-dimethylborepane	81	76-79(20)	39
B-(β-Dimethylaminoethoxy)-3,6-dimethylborepane	95	104-105(1)	39
B-Methoxy-9-BBN	87	30-33(0.08)	63
B-(n-Butoxy)-9-BBN	90	99-105(1-2)	70
B-(2-Aminoethoxy)-9-BBN	95	Mp 201-204	67
B-Methoxy-2-borabicyclo-[3.3.1]nonane	56	30-32(0.2)	33a
B-Methoxy-4,8-dimethyl-2-borabicyclo[3.3.1]nonane	74	39-44(0.15-0.2)	33a

[a,b] See the corresponding footnotes in Table VI.



Methanolysis of the mixture of **62** and **69**, followed by fractional distillation, provides B-methoxyborepane (~95% pure), b.p. 74–76°C (32 mm), in 84% yield based on 1,5-hexadiene.[34]



3. *Other monocyclic organoboranes*

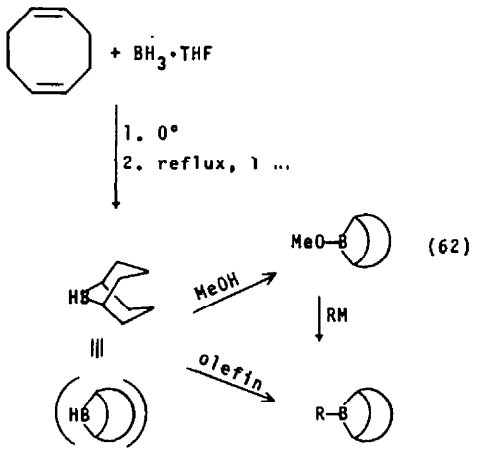
No 3- or 4-membered organoboranes appear to have been reported. Based on the properties of borolane and its derivatives, the small-membered organoboranes are expected to be highly labile. Similarly, no parent boracyclanes containing eight or more ring atoms have been reported, although certain B-methoxyboracyclanes have been obtained as isomeric mixtures (Section III.C.2).

4. *Bis(9-borabicyclo[3.3.1]nonane)* (9-BBN), B-*alkyl*-9-BBN, *and* B-*alkoxy*-9-BBN

As discussed in Section III.B.4. the hydroboration of 1,5-cyclooctadiene with borane–THF in a 1:1 ratio followed by refluxing the mixture for 1 hr produces a solution containing 9-BBN.[40] The yield realized in this manner is ~90%. In many cases, this product is satisfactory as a reagent for subsequent reactions. However, it can also be readily purified either by recrystallization (m.p. 150–152°C in a sealed capillary under nitrogen) or by distillation (b.p. 195°/12 mm). 9-BBN is now commercially available.[5]

Methanolysis of 9-BBN provides B-methoxy-9-BBN, and the hydroboration of olefins with 9-BBN produces B-alkyl-9-BBN in quantitative yields, except when olefins are highly hindered or highly unreactive for other reasons.[40] Alternatively, B-methoxy-9-BBN can be treated with appropriate organometallics, such as those containing Li, Mg, and Al, to give B-alkyl-9-BBN.[63] These are summarized in eqn (62).

Crystalline 9-BBN possesses remarkable thermal stability. Thus, it can be stored under dry nitrogen indefinitely at room temperature without any loss in activity. It is also relatively stable to air and moisture.



However, it is recommended that all manipulations of the reagent be carried out in an inert atmosphere, since its impurities or the products derived from it, are frequently highly pyrophoric. 9-BBN is soluble in most organic solvents, its solubility at 25°C ranging from 0.36 to 0.81 moles/l in representative solvents: decane, 0.36; ethyl ether, 0.39; heptane, 0.43; pentane, 0.48; hexane, 0.52; methylene chloride, 0.56; THF, 0.62; *o*-xylene, 0.63; toluene, 0.72; and benzene, 0.81. However, its solubility in diglyme is only 0.01 moles/l.[64]

V. UNIQUE APPLICATIONS OF BORACYCLANES AND THEIR DERIVATIVES TO ORGANIC SYNTHESIS

Boracyclanes (bisboracyclanes) and their B-alkyl and B-alkoxy derivatives have recently found a number of unique applications in organic synthesis. In cases where the boracyclane moiety is not incorporated in the desired product, such a boracyclane may conveniently be viewed as a *reagent*. In other cases, it may be considered as an *intermediate*.

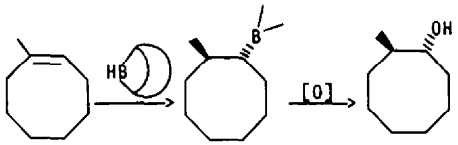
A. 9-BBN As a Reagent

Because of the ready availability of the starting diene, 1,5-cyclooctadiene, the ease of preparation, its unusual stability and, last but not least, its unique chemical properties, 9-BBN has proved to be by far the most useful bisboracyclane prepared to date.

1. 9-BBN *as a selective hydroborating agent and its application to alcohol synthesis*

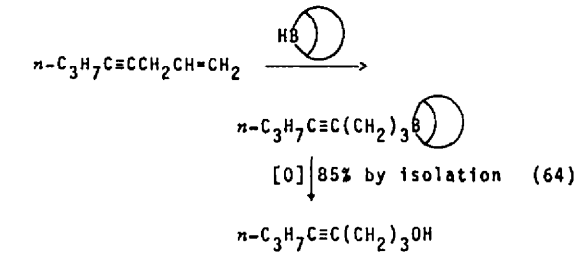
All dialkylboranes appear to exhibit considerably greater regioselectivity than borane complexes or monoalkylboranes, as discussed in Section II. The regioselectivity observed with 9-BBN[40] is at least comparable to that with other dialkylboranes, such as disiamylborane, dicyclohexylborane and diisopinocamphenylborane (dipinanylborane), as discussed in detail in one of our recent publications.[40b] However, in many cases, 9-BBN offers unique advantages over other dialkylboranes. Because of its unusual stability, especially with respect to dehydroboration, disproportionation and isomerization, it is the reagent of choice in cases where olefins to be hydroborated are hindered, such as tri- and tetrasubstituted olefins. In most cases, the expected B-alkyl-9-BBN's can be obtained quantitatively. Furthermore, the B-alkyl-9-BBN's are considerably more stable with respect to dehydroboration, isomerization or disproportionation. Thus, even 1-methylcyclooctene can be cleanly con-

verted to *trans*-2-methylcyclooctanol in 90% yield[65] (eqn 63), whereas borane–THF provides a mixture of regio- and stereo-isomers.



90% (63)

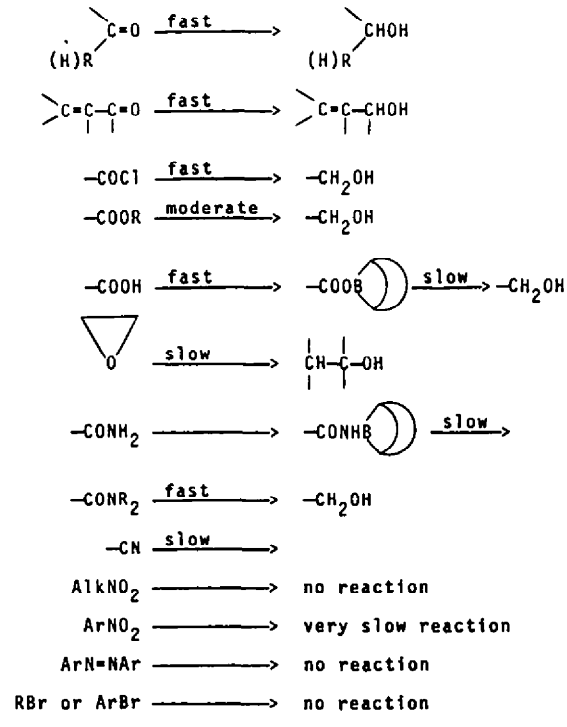
The hydroboration of 1-octen-4-yne with 1 equiv of 9-BBN produces B-4-octynyl-9-BBN, essentially free of other isomeric products, in 85% yield[66] (eqn 64), whereas the corresponding reaction with disiamylborane or dicyclohexylborane appears complicated by competitive hydroboration of the triple bond.



(64)

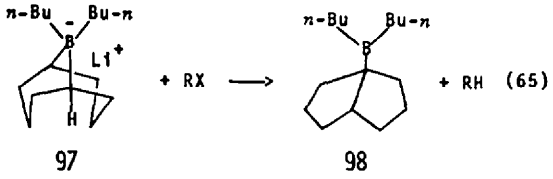
2. 9-BBN *as a selective reducing agent*

The reducing properties of 9-BBN have recently been delineated.[67] These characteristics may be summarized as follows.

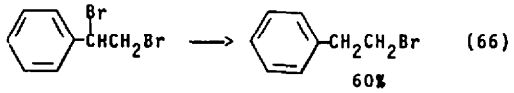


α,β-Unsaturated aldehydes and ketones can readily be converted to the corresponding allylic alcohols without reducing the C=C double bond.[68] The reduction of free carboxyl groups to alcohols in peptides using 9-BBN has been reported.[69]

It has recently been observed that the "ate" complex obtained by the reaction of a B-alkyl-9-BBN with an alkyllithium possesses unique reducing characteristics, one of the bridge-head hydrogens acting as a hydride. Thus, the reagent selectively reduces tertiary alkyl, benzyl and allyl halides to hydrocarbons without reducing simultaneously primary and secondary alkyl and aryl halides[70a] (eqns 65 and 66). The boron-containing product has been identified as **98**.[71]



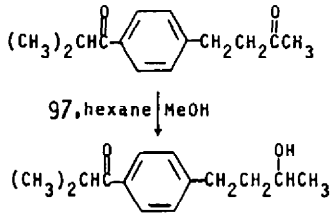
(65)



(66)

The coplanar relationship of the $C_{(1)}$–B–$C_{(5)}$–H moiety must be at least partially responsible for the unexpectedly facile hydride transfer.

The "ate" complex **97** also exhibits high regio- and chemoselectivity in the reduction of carbonyl derivatives, as indicated by the following example[70b] (eqn 67).

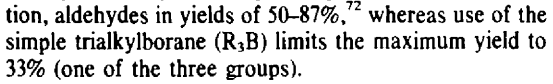


(67)

3. 9-BBN *as a non-participating blocking ("Dummy") group*

In many reactions of organoboranes, only one of the three or four organic groups is incorporated into the disired products. It is, therefore, of critical significance to find a suitable organoborane reagent, the organic group of which does not participate in the reaction in question. The results obtained to date indicate that there is no generally applicable borane reagent currently available for this purpose, various borane derivatives, such as thexylborane, monochloroborane-ethyl ether, dichloroborane-ethyl ether, disiamylborane, dicyclochexylborane, 9-BBN and 3,5-DMBN being complementary to one another. Those organoborane reactions in which 9-BBN has been effective as a blocking group are briefly discussed below.

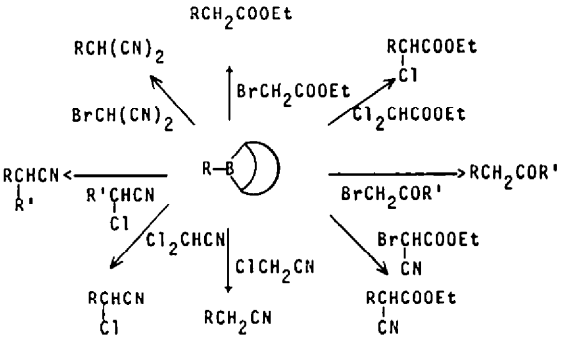
Carbonylation. The reaction of B-alkyl-9-BBN with carbon monoxide in the presence of lithium tri-*tert*-butoxyaluminohydride (eqn 68) produces, after oxidation, aldehydes in yields of 50–87%,[72] whereas use of the simple trialkylborane (R_3B) limits the maximum yield to 33% (one of the three groups).



(68)

The precise reason for the reluctance of the 9-BBN group to participate in the carbonylation reaction is not yet clear.

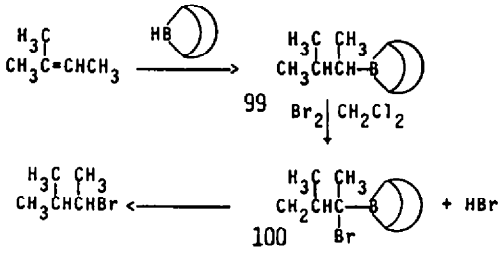
Alkylation. The B-alkyl groups of B-alkyl-9-BBN's are selectively transferred in the reaction with various α-halo ketones, esters, and nitriles under the influence of a base, such as potassium *tert*-butoxide or potassium 2,6-di-*tert*-butylphenoxide[73] (eqn 69).



(69)

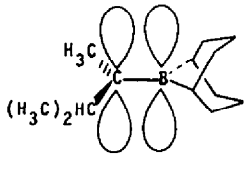
Here again, no satisfactory explanation appears available to account for selectivity observed in these reactions. Especially puzzling and disturbing is the fact that the 9-BBN moiety participates competitively in a related alkylation reaction with diazo ketones.[74] A detailed review of alkylation with organoboranes has been published.[75]

Bromination. B-Alkyl-9-BBN's derived from internal olefins, such as B-(3-methyl-2-butyl)-9-BBN (**99**), are selectively brominated on the carbon directly bonded to the boron of the B-alkyl group to give **100**, which is further converted to the corresponding alkyl bromide. The reaction provides a convenient method for the conversion of internal olefins into bromides [76a] (eqn 70).



(70)

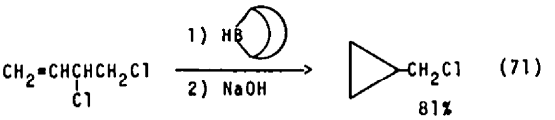
The bromination evidently proceeds via the free radical intermediate **101** which is resonance-stabilized.[76b] Abstraction of one of the bridgehead hydrogens is not favored, presumably because it would produce a free radical **102** which is orthogonal to the empty *p* orbital of the boron. Therefore, the high selectivity observed may be unique to 9-BBN.



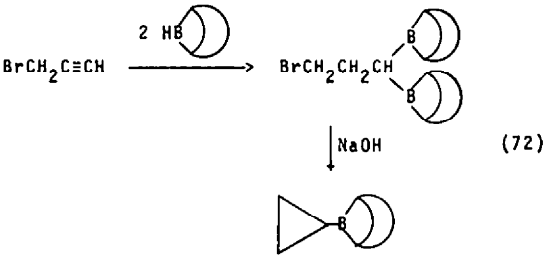
101

102

Cyclopropane synthesis. Although the following cyclopropane syntheses can, in principle, be achieved with other dialkylboranes, 9-BBN has provided the most favorable results[77] (eqns 71 and 72).



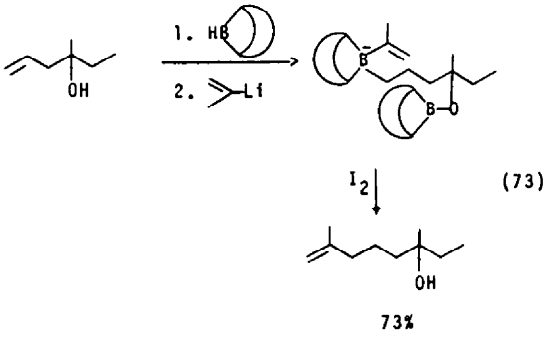
(71)



(72)

The latter reaction, which provides a simple route to B-cyclopropyl-9-BBN, is adaptable to the synthesis of B-cyclobutyl, B-cyclopentyl, and B-cyclohexyl derivatives, as well.[78]

Olefin synthesis via iodination. In the following olefin synthesis, 9-BBN acts as an effective blocking group[79] (eqn 73).



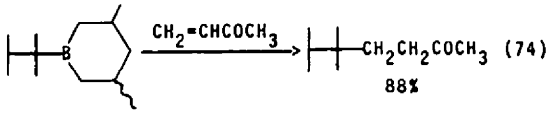
(73)

B. Borinanes and borepanes as reagents

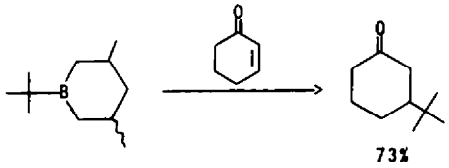
Borinanes (or bisborinanes) (**60**, **63**, **93**) and borepanes (or bisborepanes) (**62**, **64**) are unique in that they may be viewed as dialkylboranes with two primary alkyl groups, and yet are stable to disproportionation, whereas acyclic dialkylboranes with two primary alkyl groups are highly unstable in this respect. These boracyclanes have found unique applications in certain free-radical and ionic reactions of organoboranes.

1. *Free radical reactions*

Conjugate addition reactions. In the reaction of α,β-unsaturated aldehydes and ketones with organoboranes, only one of the three alkyl groups is utilized.[80] This difficulty can be overcome using B-alkylborinanes and B-alkylborepanes provided that the B-alkyl groups are secondary or tertiary,[39a,81] as shown in eqns (74) and (75).



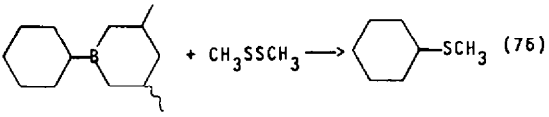
(74)



(75)

These reactions presumably involve a bimolecular homolytic substitution reaction (S_H2 reaction),[80] and tertiary and secondary alkyl free radicals are more readily formed than primary alkyl radicals. 3,5-Dimethylborinane (3,5-DMBN) is the easiest to prepare and tends to give the most favorable results. However, the starting diene, 2,4-dimethyl-1,4-pentadiene is at present relatively expensive.

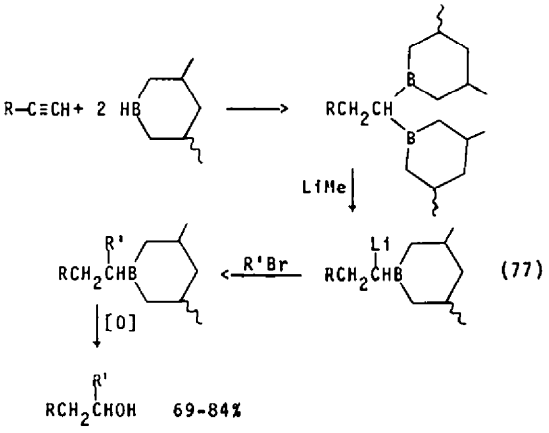
Other free-radical reactions. The mechanistic consideration presented above suggests that any other S_H2 reactions of organoboranes[80] are likely to give improved results by the use of borinanes and borepanes, as indicated by the following synthesis of sulfides[82] (eqn 76).



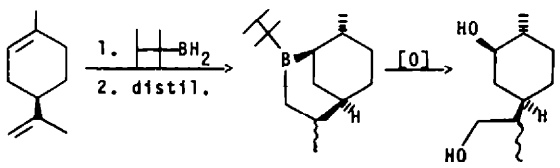
(76)

2. *Ionic reactions*

Treatment of a terminal acetylene with two equivalents of a dialkylborane followed by addition of methyllithium generates a species which acts as a boron-stabilized carbanion. Its reaction with an alkyl halide followed by oxidation produces the corresponding secondary alcohol.[83] Although various dialkylboranes can be used, boracyclanes such as 3,6-dimethylborepane and 9-BBN offer an advantage in that only one equivalent of methyllithium is required. When dicyclohexylborane is used, two equivalents of methyllithium are needed, and the yields are considerably lower.



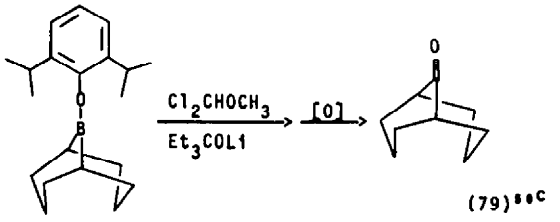
(77)



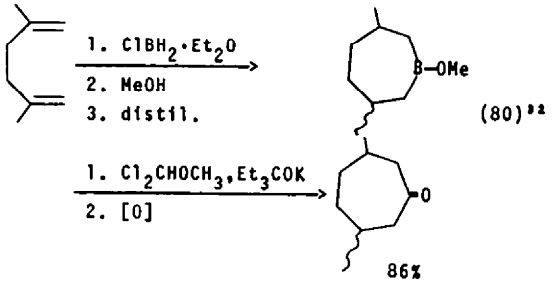
(78)

2. *Carbonylation, carbenation* (DCME), *and cyanoboration*

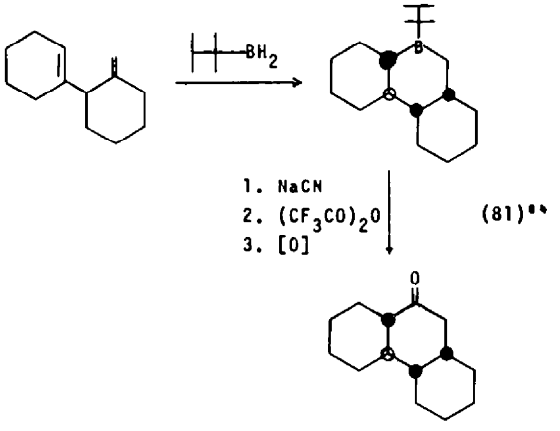
These reactions have been adequately discussed in previous sections. Furthermore, the carbonylation[16] and the cyanoboration[49] reactions have been reviewed comprehensively. In addition to the examples presented in previous sections (eqns 14, 15, 19, 43–45, 49), the following are presented to further demonstrate their synthetic utilities.



(79)[84c]



(80)[82]



(81)[84]

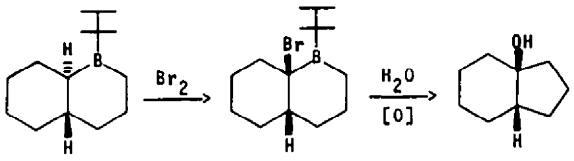
C. ORGANOBORANE HETEROCYCLES AS INTERMEDIATES

1. *Regio- and stereoselective alcohol synthesis*

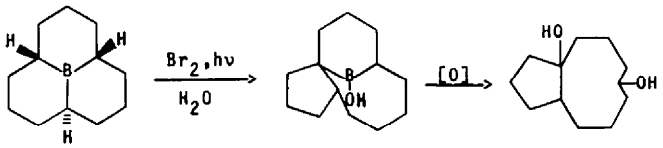
Cyclic hydroboration offers highly regio- and stereoselective methods for the conversion of dienes and polyenes into diols and polyols, as indicated by the conversion of 1,5-cyclooctadiene into *cis*-1,5-cyclooctanediol (eqn 17) and by the following conversion of D-(+)-limonene (**26**) into the *cis*-diol **27**[41] (eqn 78).

3. *Bromination*

The free-radical α-bromination of organoboranes in the presence of a suitable nucleophile, such as water, provides a unique method for C–C bond formation.[85] Its application to organoborane heterocycles has provided a number of cyclic alcohols not readily available by other routes. The following examples are representative.[86]



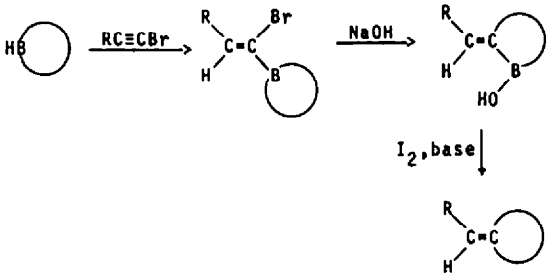
(82)

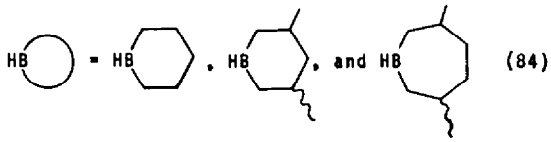


(83)

4. *Exocyclic olefin synthesis*

The following represents another unique synthesis of carbocyclic skeletons via boracyclanes[87] (eqn 84).

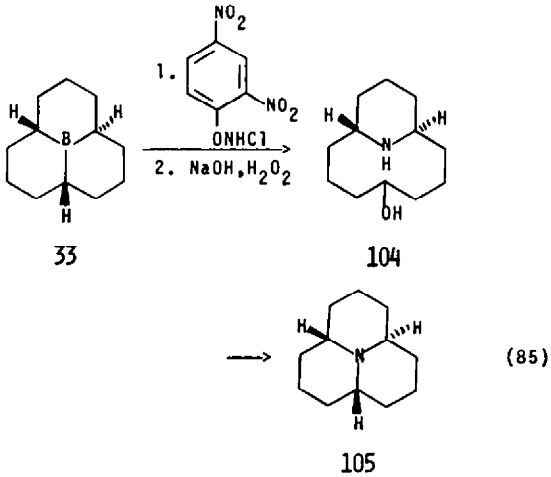




(84)

5. *Amination*

Recently, perhydro-9b-boraphenalene (**33**) has been converted to the bicyclic and tricyclic amines **104** and **105**, opening up an attractive entry into cyclic amines including certain alkaloids[88] (eqn 85).



(85)

VI. CONCLUSIONS

It is evident that considerable progress has been made in developing methods to achieve the synthesis of boraheterocyclics by the hydroboration of dienes and polyenes with appropriate reagents. It has been possible to utilize such cyclic hydroboration to introduce two or three groups with stereochemically defined structures. Alternatively, the various procedures now available for the replacement of boron by carbon permit the application of boraheterocycles for the synthesis of ring systems, again with defined stereochemistry. Finally, a number of the boraheterocycles have proven to possess highly unusual properties. In some cases these derivatives are finding promising application as new reagents for hydroborations and reductions. These unusual properties have opened up a number of fascinating theoretical questions for exploration. Consequently, the study of cyclic hydroboration is opening up major new areas, of interest both practically and theoretically. Major new developments will doubtless come forth as this area is subjected to further study.

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