

REPORT DOCUMENTATION PAGE			
AD-A201 597		RESTRICTED V 2 3 1988	
1b. RESTRICTIVE MARKINGS		3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) H		5. MONITORING ORGANIZATION REPORT NUMBER(S) ARO 22913-9-CH	
6a. NAME OF PERFORMING ORGANIZATION The Ohio State University Research Foundation	6b. OFFICE SYMBOL (if applicable)	7a. NAME OF MONITORING ORGANIZATION U. S. Army Research Office	
6c. ADDRESS (City, State, and ZIP Code) 1314 Kinnear Rd., Columbus, Ohio 43212-1194		7b. ADDRESS (City, State, and ZIP Code) P. O. Box 12211 Research Triangle Park, NC 27709-2211	
8a. NAME OF FUNDING/SPONSORING ORGANIZATION U. S. Army Research Office	8b. OFFICE SYMBOL (if applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER DAAG29-85-K-0187	
8c. ADDRESS (City, State, and ZIP Code) P. O. Box 12211 Research Triangle Park, NC 27709-2211		10. SOURCE OF FUNDING NUMBERS	
		PROGRAM ELEMENT NO.	PROJECT NO.
		TASK NO.	WORK UNIT ACCESSION NO.
11. TITLE (Include Security Classification) Studies on Syntheses and Derivatives of Boron Hydride Systems			
12. PERSONAL AUTHOR(S) Dr. Sheldon G. Shore			
13a. TYPE OF REPORT Final	13b. TIME COVERED FROM 85/6/1 TO 88/8/31	14. DATE OF REPORT (Year, Month, Day) 88/10/25	15. PAGE COUNT 33
16. SUPPLEMENTARY NOTATION The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.			
17. COSATI CODES		18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)	
FIELD	GROUP	SUB-GROUP	
		pentaborane (9), B ₅ H ₉ , [B ₉ H ₁₄] ²⁻ , [B ₁₁ H ₁₄] ⁻ , borane anions, aluminaborane, phosphaborane, boron nitride precursor, lanthanide borane - 225	
19. ABSTRACT (Continue on reverse if necessary and identify by block number)			
<p>Studies of reaction pathways in the conversion of B₅H₉ to [B₉H₁₄]²⁻ resulted in maximizing the yield of [B₉H₁₄]²⁻ and a close to quantitative synthesis of [B₁₁H₁₄]⁻. The [B₉H₁₃]²⁻ dianion derived from [B₉H₁₄]²⁻ has been synthesized and characterized. The heteraboranes [B₁₁H₁₁AlCH₃]²⁻, B₁₁H₁₁PCH₃, and B₁₀H₁₂PCH₃ derived from [B₁₁H₁₄]⁻ have been synthesized and characterized. Alkali metal reductions of B₅H₉ and THFBH₃ result in the dianions [B₅H₉]²⁻ and [BH₃]²⁻. A cage expansion reaction has produced a 10 vertex arachino-C₂B₈ carborane. The lanthanides Yb, Eu, Sm reduce B₁₀H₁₄ to form lanthanide boranes precursors of lanthanide borides. Reduction of the boron nitride precursor Cl₂B₃N₃H₃ has been investigated.</p>			
20. DISTRIBUTION/AVAILABILITY OF ABSTRACT <input type="checkbox"/> UNCLASSIFIED/UNLIMITED <input type="checkbox"/> SAME AS RPT. <input type="checkbox"/> OTIC USERS		21. ABSTRACT SECURITY CLASSIFICATION Unclassified	
22a. NAME OF RESPONSIBLE INDIVIDUAL Dr. Sheldon G. Shore		22b. TELEPHONE (Include Area Code) 614-292-6000	22c. OFFICE SYMBOL

STUDIES ON SYNTHESIS AND DERIVATIVES
OF BORON HYDRIDE SYSTEMS

FINAL REPORT

For the Period

July 1, 1985 - August 31, 1988

Sheldon G. Shore

October 25, 1988

U. S. ARMY RESEARCH OFFICE

Research Triangle Park, North Carolina 27709

Grant No. DAAG29-85-K-0187

The Ohio State University Research Foundation

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Contents

	Page
I. Studies of Reaction Pathways in the Conversion of Pentaborane(9) to $[B_9H_{14}]^-$	1
II. High-Yield Preparation of the $[B_{11}H_{14}]^-$ Ion From Pentaborane(9)	4
III. $[B_9H_{13}]^{2-}$ a Derivative of $[B_9H_{14}]^-$	7
IV. Alumina- and Phospha- Derivatives of $[B_{11}H_{14}]^-$	10
V. Reduction of Boron Hydrides by Alkali Metals	16
VI. Formation of <u>arachno</u> -6-((CH ₃) ₃ Si)-6,9-C ₂ B ₈ H ₁₃ through a Cage-Expansion Reaction	21
VII. Boron Nitride Precursors	23
VIII. Reduction of Decaborane(14) by the Lanthanide Metals; Precursors to Lanthanide Borides	24
Bibliography	25
List of Publications Resulting from ARO Support	28
List of Participating Scientific Personnel	30



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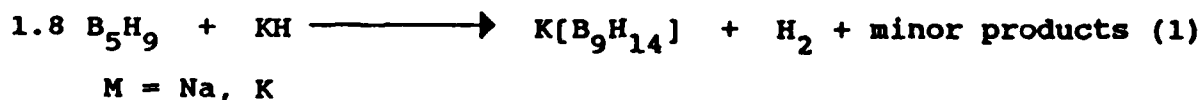
Forward

In recent times, one of our primary goals has been to convert pentaborane(9), B_5H_9 , into potentially useful products. This is a desirable goal in view of the fact that some 200,000 lbs of B_5H_9 have been in Government storage since the 1950's. Under an earlier grant from ARO we developed a practical procedure for the conversion of B_5H_9 to $B_{10}H_{14}$, an important precursor to a number of potentially useful materials such as burn rate accelerators and energy transfer devices. We also found during our studies of B_5H_9 to $B_{10}H_{14}$ conversion, that some of the boron hydride and carborane materials traditionally prepared from $B_{10}H_{14}$ could be prepared in "one-pot" syntheses from B_5H_9 without preparing $B_{10}H_{14}$ as an intermediate.

From the present grant, we report results of continued studies in the conversion of B_5H_9 to potentially useful materials. We have studied reaction pathways in the conversion of B_5H_9 to $[B_9H_{14}]^-$, and have not only maximized the yield of this anion but have also developed an essentially quantitative conversion of B_5H_9 to $[B_{11}H_{14}]^-$. We have undertaken the study and development the chemistry of these anionic materials obtained from B_5H_9 and related boron hydrides. Furthermore, in the later stages of the grant period we expanded the program to include studies on the formation of precursors to lanthanide boride and boron nitride precursors. Our research activities are summarized in eight sections. Each section contains a preamble which provides a statement of the problem studied.

I. Studies of Reaction Pathways in the Conversion
of Pentaborane(9) to $[B_9H_{14}]^-$

The tetradecahydrononaborate(1-) ion $[B_9H_{14}]^-$, is useful in the syntheses of boranes,^{1,2,3,4} carboranes, and metallaboranes.⁴⁻¹³ The most widely employed preparations of $[B_9H_{14}]^-$ rely on base degradation of $B_{10}H_{14}$;¹⁵ however, it has also been formed in good yield (60%) from the decomposition of $[B_5H_8]^-$ in glyme.¹⁶⁻¹⁹ Interest in B_5H_9 as a starting material for the preparation of higher boron hydrides and carboranes prompted our research to improve the preparation of $[B_9H_{14}]^-$ from B_5H_9 .^{3,4,19} The method we have developed and published² for the preparation of $[B_9H_{14}]^-$ from B_5H_9 is superior to that reported previously¹⁶⁻¹⁸ since the yield of $[B_9H_{14}]^-$ is maximized, the production of side products is suppressed, and reaction times are shorter. The optimum ratio of reactants was found to be 1.8 $B_5H_9/1$ KH (Reaction (1)).



The initial step in this reaction is deprotonation of B_5H_9 to form $[B_5H_8]^-$. Boron-11 NMR spectroscopy was employed to follow the course of the reaction as a function of mole ratio of reactants. All of the B_5H_9 was consumed at a molar ratio of 1.8 $B_5H_9/1$ KH. With increasing ratio of reactant from 1/1 to the optimum value of 1.8/1 the yield of $[B_9H_{14}]^-$ increased and side reactions were

$[\text{B}_3\text{H}_8]^-$ and $[\text{BH}_4]^-$ as minor products, pathway 3). In the presence of excess B_5H_9 it was shown that pathway 1) takes precedence over pathway 2).

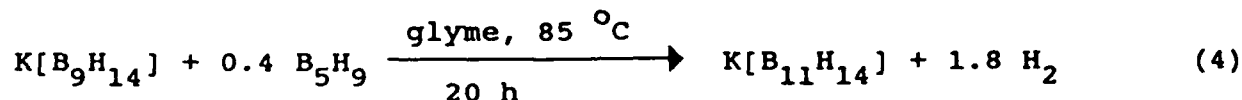
Investigation of Reaction (1) as a function of time at room temperature confirmed the above results. Rapid formation of $[\text{B}_9\text{H}_{14}]^-$ and the absence of detectable signals for $[\text{B}_5\text{H}_8]^-$, as followed by boron-11 NMR, spectroscopy were the most striking features of this study. Although B_5H_9 and $\text{K}[\text{B}_5\text{H}_8]$ coexist in THF solutions without reacting at temperatures below -40°C , at room temperature, $[\text{B}_5\text{H}_8]^-$ reacts very rapidly with B_5H_9 and with other species such as BH_3THF which are generated in solution. Within a few minutes of the onset of reaction, $[\text{B}_9\text{H}_{14}]^-$ is the predominant species in solution. The yield of $[\text{B}_9\text{H}_{14}]^-$ increases only slowly thereafter, apparently the result of a number of slower side reactions. High yields (70-80% based upon the B_5H_9 starting material) were achieved in relatively short (6-10 hours) reaction times.

The tetramethylammonium salt of $[\text{B}_9\text{H}_{14}]^-$ was readily obtained from Reaction (1) by the addition of one equivalent of $[(\text{CH}_3)_4\text{N}]\text{Cl}$ to the reaction pot, according to Reaction (3).

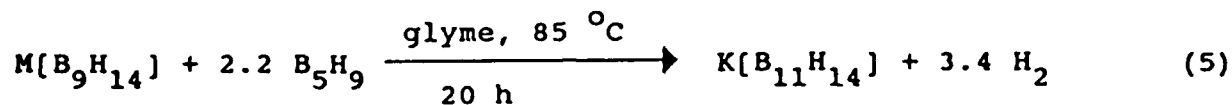


II. High-Yield Preparation of the of the $[B_{11}H_{14}]^-$ Ion From Pentaborane(9)

In the course of our studies of reaction pathways in the conversion of pentaborane(9) to $[B_9H_{14}]^-$, described above,² we found that when an excess quantity of B_5H_9 was employed in the preparation of $[B_9H_{14}]^-$ (Reaction (1)), $[B_{11}H_{14}]^-$ would form after long reaction times. Furthermore, formation of $[B_{11}H_{14}]^-$ accelerated with increasing temperature. These initial observations suggested that the reaction between B_5H_9 and $[B_9H_{14}]^-$ would lead to the formation of $[B_{11}H_{14}]^-$. Indeed, a quantitative yield of $K[B_{11}H_{14}]$ was obtained from the stoichiometry and conditions shown in Reaction (4).



Since we have shown that $K[B_9H_{14}]$ is readily produced from the reaction of 1.8 equivalents of B_5H_9 with KH or NaH in glyme at room temperature, it was convenient to adapt this procedure to a "one-pot" synthesis of $[B_{11}H_{14}]^-$ from B_5H_9 by altering the ratio of reactants and increasing the reaction temperature.²⁰ When B_5H_9 and KH were reacted in a 2.4:1 molar ratio in glyme at 85 °C, the only nonvolatile boron hydride product was $K[B_{11}H_{14}]$, as indicated from its boron-11 nmr spectrum. The reaction is essentially quantitative based on $K[B_{11}H_{14}]$ produced and H_2 gas evolved in the reaction. Similar results are obtained when NaH is used in place of KH and the reaction can be represented by that shown in Reaction (5).



In a similar reaction $Li[B_{11}H_{14}]$ was prepared from t -BuLi and B_5H_9 . When B_5H_9 and t -BuLi were reacted in a 2.4:1 molar ratio in glyme at 85°C , the major nonvolatile boron-containing product (>85%) was $Li[B_{11}H_{14}]$, as indicated from its boron-11 NMR spectrum.

In addition to the preparative reactions cited above, it was found that 1 equivalent of B_2H_6 also reacts with $K[B_9H_{14}]$ under the same conditions to produce $[B_{11}H_{14}]^-$ in essentially quantitative yield based upon analysis of the volatiles and the boron-11 NMR spectrum of the nonvolatile product. Although the reaction of B_5H_9 with $Na[BH_4]$ has been previously shown²¹ to produce $[B_{11}H_{14}]^-$, this preparation provides much lower yields of $[B_{11}H_{14}]^-$ along with other anionic species ($[B_3H_8]^-$ and $[B_{12}H_{12}]^{2-}$) and employs the use of high pressure equipment. The procedure we have developed produces pure $[B_{11}H_{14}]^-$ in yields that are in excess of 90% based on B_5H_9 and is carried out in standard Pyrex laboratory apparatus. It is especially attractive in view of the large stockpile of B_5H_9 in government inventories.

The molecular structure of the $[B_{11}H_{14}]^-$ anion was determined from a single crystal X-ray study²² of the $[P(CH_3)_3H][B_{11}H_{14}]$ salt. The boron framework of the $[B_{11}H_{14}]^-$ anion (Figure 1) is based upon a regular icosahedral structure with one vertex

removed. The structure has pseudo- C_s symmetry. An interesting feature of this structure is the arrangement of the three hydrogen atoms associated with the open face of the cage that are not exo-terminal hydrogens. Early in the development of polyhedral borane chemistry it was suggested²³ that the $[B_{11}H_{14}]^-$ ion could be described as a H_3^+ triangle interacting with a $[B_{11}H_{11}]^{2-}$ fragment, while a later structural prediction²⁴ assumed that two of the three hydrogens would bridge boron atoms while the third hydrogen would be an endo-terminal hydrogen. The structural results confirm this later prediction. Figure 1B clearly shows That H(13) is an endo-terminal hydrogen and H(12) and H(14) are bridge hydrogens.

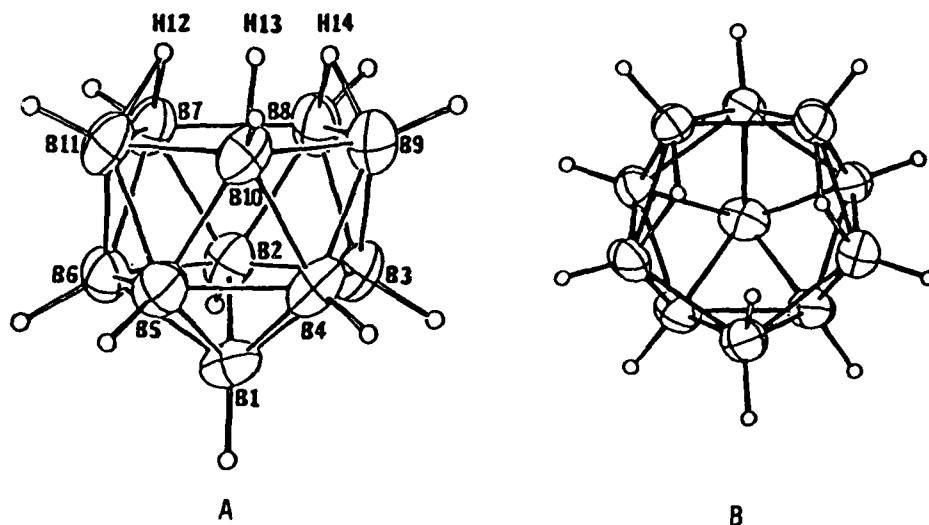
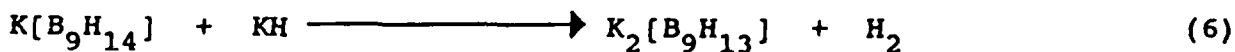


Figure 1. Views of the molecular structure of $[B_{11}H_{14}]^-$ (ORTEP plots with 50% probability ellipsoids).

III. $[\text{B}_9\text{H}_{13}]^{2-}$ a Derivative of $[\text{B}_9\text{H}_{14}]^-$

Nido- $[\text{B}_n\text{H}_{n+2}]^{2-}$ and arachno- $[\text{B}_n\text{H}_{n+4}]^{2-}$ dianions have received much less attention²⁵⁻²⁸ than closo- $[\text{B}_n\text{H}_n]^{2-}$ dianions.²⁹ Only two arachno-dianions, $[\text{B}_5\text{H}_9]^{2-}$ and $[\text{B}_{10}\text{H}_{14}]^{2-}$, prepared by the two-electron reduction of B_5H_9 ²⁵ and $\text{B}_{10}\text{H}_{14}$ ²⁸ have been studied in any detail. Preparation of arachno- $[\text{B}_9\text{H}_{13}]^{2-}$ was reported several years ago through deprotonation of $\text{Cs}[\text{B}_9\text{H}_{14}]$ by butyl lithium. While some chemical properties were described, no structural or spectroscopic details were given for $[\text{B}_9\text{H}_{13}]^{2-}$. In view the previous limited characterization of this anion and in view of our procedure for preparing $[\text{B}_9\text{H}_{14}]^-$ from B_5H_9 , we developed a synthesis for the potassium salt of $[\text{B}_9\text{H}_{13}]^{2-}$ and characterized it in some detail.

The reaction of $\text{K}[\text{B}_9\text{H}_{14}]$ with KH in glyme produces $\text{K}_2[\text{B}_9\text{H}_{13}]$ in high yield (90%), Reaction (6). This salt is air sensitive.

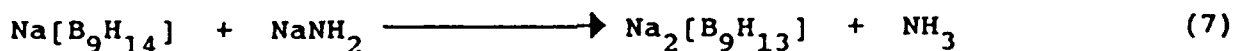


However, it is stable under an N_2 atmosphere for periods of several months without noticeable decomposition. When heated to 60°C for 48 hours slight decomposition is observed by boron-11 NMR spectroscopy. At 100°C , significant decomposition occurs with the formation of a variety of closo-boron hydride dianions:

$[\text{B}_{10}\text{H}_{10}]^{2-}$ (27%), $[\text{B}_9\text{H}_9]^{2-}$ (16%), $[\text{B}_7\text{H}_7]^{2-}$ (14%), $[\text{B}_{12}\text{H}_{12}]^{2-}$ (11%), of the total boron was determined by boron-11 NMR

spectroscopy. Also present is some $[\text{BH}_4]^-$ (5%) plus a species believed to be $[\text{B}_{10}\text{H}_{14}]^{2-}$ (27%) with ^{11}B resonances of -6.0 ppm (d, J = unresolved), -21.3 ppm (d, J = 102 Hz), -34.1 ppm (t, J = unresolved), and -40.3 ppm (d, J = 123 Hz) where $\delta(\text{BF}_3\text{OEt}_2) = 0.00$ ppm. The potassium salt is insoluble in THF and glyme, but it is soluble in NH_3 . It is also soluble in CH_3CN when the potassium cations are complexed by Krypt2.2.2. In THF a slurry of $\text{K}_2[\text{B}_9\text{H}_{13}]$ apparently reduces $\text{Ti}(\text{C}_5\text{H}_5)_2\text{Cl}_2$ with the formation of the $[\text{B}_9\text{H}_{12}]^-$ anion and reacts with neat $\text{Si}(\text{CH}_3)_2\text{Cl}_2$ to form $n\text{-B}_{18}\text{H}_{22}$.

Attempted deprotonation of $\text{Na}[\text{B}_9\text{H}_{14}]$ by NaH in glyme was very sluggish, even at 40 °C. Therefore, $\text{Na}_2[\text{B}_9\text{H}_{13}]$ was prepared through the deprotonation of $\text{Na}[\text{B}_9\text{H}_{14}]$ by $\text{Na}[\text{NH}_2]$ in liquid ammonia (Reaction (7)). It is soluble in NH_3 , THF, and glyme.



Several unaccounted for explosions which occurred during the preparation of $\text{Na}_2[\text{B}_9\text{H}_{13}]$ and the precursor salt $\text{Na}[\text{B}_9\text{H}_{14}]$ caused us to abandon further study of these salts.

The structure of the $[\text{B}_9\text{H}_{13}]^{2-}$ ion was determined (Figure 2) from a single crystal X-ray diffraction study of the $[\text{Krypt2.2.2.K}]_2[\text{B}_9\text{H}_{13}]$ salt. The basic structure of $[\text{B}_9\text{H}_{13}]^{2-}$ is similar to that of $[\text{B}_9\text{H}_{14}]^-$.³⁰ Its boron framework can be derived from the $\text{B}_{10}\text{H}_{14}$ framework by removing either one of the

equivalent B(6) or B(9) boron atoms. There are four endo-hydrogens in the structure. They are disordered over five positions on five boron atoms, indicated by dotted circles in Figure 2, and are assigned occupancies of 0.8. These hydrogens as well as the nine

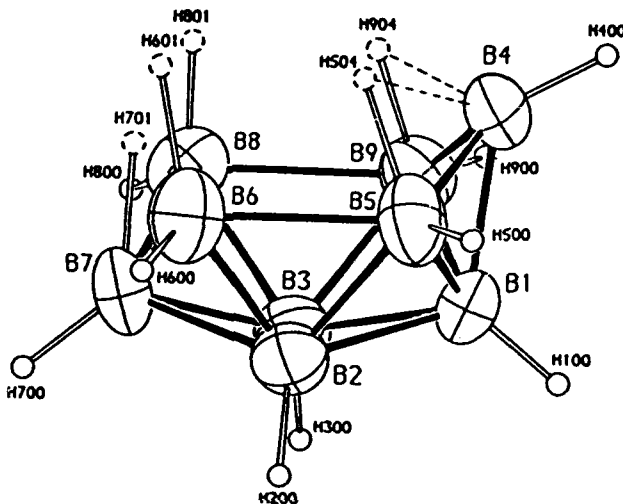


Figure 2. The structure of the $[B_9H_{13}]^{2-}$ dianion (ORTEP plot with 50% probability ellipsoids). Disordered H atoms indicated by dotted circles. Semi-bonds indicated by dotted lines.

exo-hydrogens were located on difference maps and refined. Disorder of the endo-hydrogens in the crystal implies the existence of isomers in the solid state and is compatible with the fact that these hydrogens are fluxional in solution. Five isomers (two enantiomeric pairs and a geometric isomer) can be derived from the X-ray structure by selective removal of endo-hydrogens.

Endo-hydrogens, including the semi-bridging hydrogens are fluxional on the boron-11 and proton NMR time scales over the temperature range -40 to -70 °C in ND₃. The boron-11 NMR spectrum of K₂[B₉H₁₃] at -40 °C consists of three doublets of relative areas 1:1:1: (-4.55 ppm (d, J = 22 Hz), -24.9 ppm (d, J = 125 Hz) and -29.0 ppm (d, J = 104 Hz) where δ(BF₃OEt₂) = 0.00 ppm. The doublet character of each signal arises from spin-coupling between each boron atom and the relatively non-fluxional exo-hydrogen atom to which it is bound. Due to the fluxional hydrogens, the ¹¹B NMR spectrum reflects the pseudo C_{3v} symmetry of the B₉ framework. There are three sets of boron atoms, each set containing three averaged boron environments: 1) B(4), B(6), B(8); 2) B(5), B(7), B(9); 3) B(1), B(2), B(3). The proton NMR spectrum, ¹¹B spin-decoupled at -60 °C in ND₃, consists of four resonances of relative areas 3:3:3:4 (1.94 ppm, 0.48 ppm, 0.35 ppm, and -2.32 ppm (δ(TMS) = 0.00 ppm) with the latter signal representing the averaged endo-hydrogen resonances.

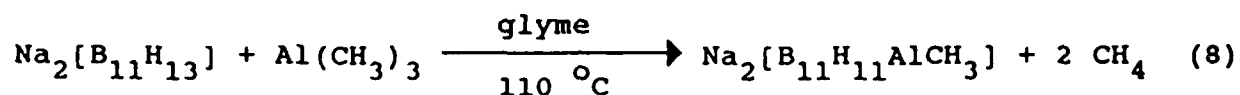
IV. Alumina- and Phospha- Derivatives of [B₁₁H₁₄]⁻

In view of our convenient high-yield synthesis²⁰ of the [B₁₁H₁₄]⁻ anion from pentaborane(9), we have investigated the use of this anion as a starting material in the preparation of alumina- and phospha- derivatives.

Prior to our work,³¹ there were no reports of aluminaboranes that are analogues of the closo-[B_nH_n]²⁻ dianions. Described

herein is the high-yield synthesis, characterization and molecular structure of the 1-methyl-1-aluminaundecahydrododecaborate(2-)dianion, $[B_{11}H_{11}AlCH_3]^{2-}$, an aluminaborane analogue of the closo- $[B_{12}H_{12}]^{2-}$ dianion.

When $Na_2[B_{11}H_{13}]$, formed from the deprotonation of $Na[B_{11}H_{14}]$, is heated in liquid $Al(CH_3)_3$ in the presence of 1 equivalent of glyme, $Na_2[B_{11}H_{11}AlCH_3]$ is formed in greater than 90% yields according to Reaction (8). It is assumed that the



glyme acts as a catalyst by cleaving the $[Al(CH_3)_2]_2$ dimer. In the absence of glyme, even after 8 days, the reaction is not complete. Progress of the reaction is followed by measuring the CH_4 evolved.

The molecular structure of the closo- $[B_{11}H_{11}AlCH_3]^{2-}$ ion was determined from single crystal X-ray data obtained from the salt $[As(C_6H_5)_4]_2[B_{11}H_{11}AlCH_3]$. The structure (Figure 3) is that of an icosahedron. The aluminum-carbon vector is essentially perpendicular to the plane formed by boron atoms B2-B6, tilting just 2° from perpendicularity.

The boron-11 NMR spectrum of $Na_2[B_{11}H_{11}AlCH_3]$ ($\zeta(BF_3OEt_2) = 0.00$ ppm) consists of the following resonances which have been assigned on the basis of a 2D ^{11}B - ^{11}B NMR study: -17.8 ppm (s, J = 114 Hz), boron atoms 7-11; -18.8 ppm (d, J = 103 Hz), boron atoms 2-6; -25.5 ppm (d, J = 129 Hz), boron atom 12. The $^1H(^{11}B)$ NMR spectrum ($\zeta(TMS) = 0.00$ ppm) consists of the resonances 0.82

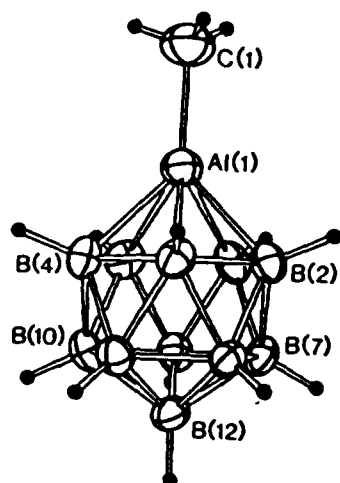


Figure 3. Molecular structure of closo-[B₁₁H₁₁AlCH₃]²⁻ (Ortep plot with 50% probability ellipsoids).

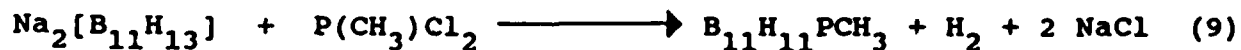
(B-H), 0.73 (B-H), and -0.64 ppm (C-H). Relative areas of these resonances are 6.2:5.2:3, respectively, in good agreement with the theoretical ratio 6:5:3, assuming that the signal due to the proton on the apical boron atom overlaps one of the other B-H signals.

Na₂[B₁₁H₁₁AlCH₃] is air-sensitive and reacts with water, producing Na₂[B₁₁H₁₃] and aluminum hydrolysis products. It also reacts with 1 equivalent of methanol at 65 °C to yield Na₂[B₁₁H₁₃] and unreacted Na₂[B₁₁H₁₁AlCH₃]. This indicates that complete cleavage of the aluminum atom from the cage is favored over the formation of species such as Na₂[B₁₁H₁₁Al(OCH₃)]. Na₂[B₁₁H₁₁AlCH₃] does not react with diethylamine or dimethylamine. This is in

contrast to the case for its carborane analogues^{32,33} $C_2B_9H_{11}AlR$ ($R = CH_3, C_2H_5$), which react with THF to form $C_2B_9H_{11}AlR \cdot THF$ and with stronger bases to cleave the aluminum atom from the cage. Solid $Na_2[B_{11}H_{11}AlCH_3]$ reacts with 1/3 equivalent of BCl_3 to yield only one polyhedral borane product and some unreacted starting material as determined by boron-11 NMR spectroscopy. The product has resonances at -13.6 (d, $J = 179$ Hz) and -15.7 ppm (br d, $J = 148$ Hz) ($\delta(BF_3OEt_2) = 0.00$ ppm). If excess BCl_3 is employed, a much more complex reaction mixture results with many overlapping resonances in the range -10 to -30 ppm being observed in the boron-11 NMR spectrum. During both reactions $B(CH_3)_3$ is evolved, indicating halide-alkyl exchange between BCl_3 and $Na_2[B_{11}H_{11}AlCH_3]$. The formation of $B(CH_3)_3$ and the simplicity of the boron-11 NMR spectrum indicate that the product formed when 1/3 equivalent of BCl_3 is employed may be the targeted compound $Na_2[B_{11}H_{11}AlCl]$.

We have prepared and determined the molecular structures of the phosphaboranes closo-1-methyl-phosphadodecaborane(11), $B_{11}H_{11}PCH_3$, and nido-7-methylphosphundecaborane(12), $B_{10}H_{12}PCH_3$.

When $Na_2[B_{11}H_{13}]$ is reacted with $P(CH_3)Cl_2$ in THF, the compound $B_{11}H_{11}PCH_3$ is obtained, Reaction (9). While this compound



is air sensitive, it is very stable, thermally. It decomposes above 220 °C in a sealed capillary. It is soluble in toluene, CH₂Cl₂, CHCl₃, CH₃CN, and it is slightly soluble in pentane and hexane. An analogous phosphaborane was reported previously,³⁴ but no structural information was given. The molecular structure of B₁₁H₁₁PCH₃ was determined from single crystal X-ray data (Figure 4). The structure consists of an icosahedron which is composed of

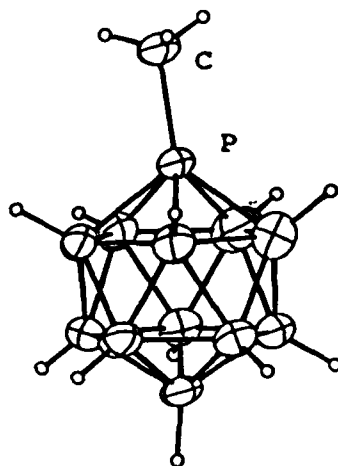


Figure 4. The molecular structure of B₁₁H₁₁PCH₃ (ORTEP plot with 50% probability ellipsoids).

a PCH₃ fragment capping a B₁₁H₁₁ unit. The P-C vector is tilted about 8° from perpendicularity with respect to the plane defined by the B2 through B6. This tilt appears to be due to packing forces rather than an electronic effect. This molecule is the analogue of the close-[B₁₂H₁₂]²⁻ dianion.

The boron-11 NMR spectrum of $B_{11}H_{11}PCH_3$ consists of the following resonances which have been assigned on the basis of a 2D ^{11}B - ^{11}B NMR study: -1.07 ppm (d, $J = 150$ Hz), boron atom 12, -6.72 ppm (d, $J = 150$ Hz), boron atoms 7-11, and -14.4 ppm (d, $J = 164$ Hz), boron atoms 2-6 ($\delta BF_3OEt_2 = 0.00$ ppm).

When diethyl ether is employed as the solvent in the reaction of $M_2[B_{11}H_{13}]$ ($M = Na, K$) with $P(CH_3)Cl_2$, the phosphaborane nido-7-methylphosphaundecaborane(12), $B_{10}H_{12}PCH_3$, is obtained. This compound was obtained previously by a different route,³⁵ but the structure was not determined. We have determined the molecular structure of $B_{10}H_{12}PCH_3$ from single crystal X-ray data. The structure, Figure 5, is derived from an icosahedron from which

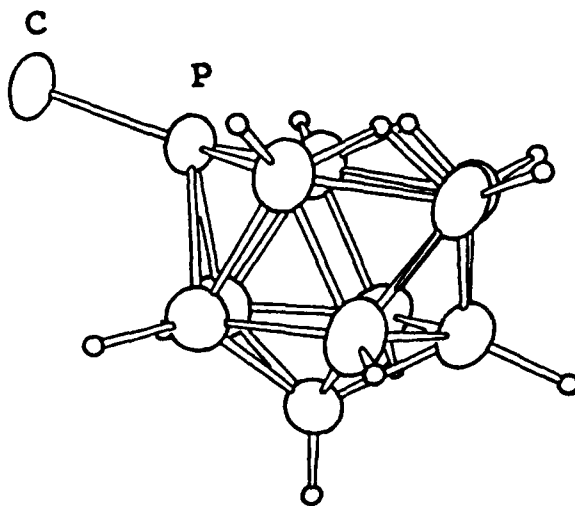


Figure 5. The molecular structure of $B_{10}H_{12}PCH_3$ (ORTEP plot with 50% thermal ellipsoids)

one vertex has been removed. The phosphorus occupies a position on the perimeter of the open face of the cage.

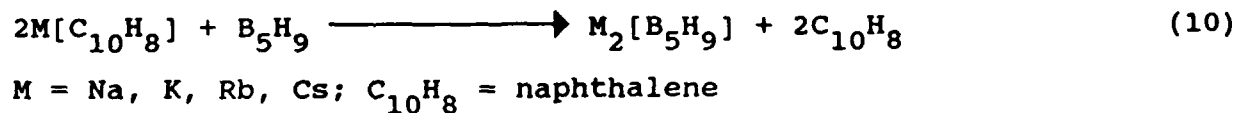
This compound is an analogue of the nido-[B₁₁H₁₃]²⁻ dianion and its structure is in accord with the predicted structure.³⁵ Although earlier work had assigned the boron-11 NMR spectrum,³⁶ we find from 2D NMR studies that some of the assignments are in fact ambiguous due to lack of coupling between boron atoms B(2,3) and B(8,11). The boron-11 NMR spectrum consists of the resonances: 3.3 ppm (d, J = 145 Hz), -7.2 ppm (d, J = 160 Hz), -11.7 ppm (d, J = 161 Hz), -16.9 ppm (d, J = 149 Hz) and -24.5 ppm (d, J = 148 Hz) (δ BF₃OEt₂) = 0.00 ppm), with relative areas of 1:2:2:2:3.

V. Reduction of Boron Hydrides by Alkali Metals

While alkali-metal reductions to produce dianions have been successfully carried out with higher boron hydrides such as B₁₀H₁₄,³⁷ reduction of the lower boron hydrides to dianions had not been demonstrated prior to our studies.³⁸ We have undertaken a study to examine the reductions of some of the smaller boron hydrides by alkali metals in the hope of obtaining new arachno-dianions. Additionally, we have examined the reduction of η -B₁₈H₂₂.

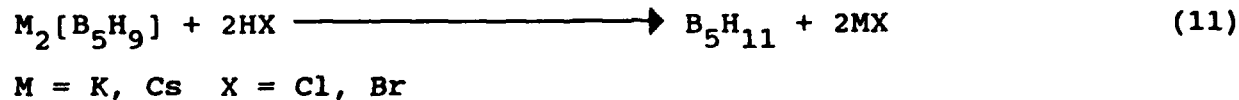
Although Stock³⁹ reported the reduction of B₅H₉ by potassium amalgam to give a compound formulated as K₂[B₅H₉], later attempts to duplicate this work showed the product to contain a large amount of K[BH₄] and unidentified materials.³⁷

We find³⁸ that B_5H_9 is cleanly reduced by two equivalents of sodium, potassium, rubidium, or cesium naphthalide in THF or glyme to form the nonahydropentaborate(2-) dianion, $[B_5H_9]^{2-}$, Reaction (10). No H_2 gas is evolved in this reaction.



The sodium salt of $[B_5H_9]^{2-}$ is slightly soluble in THF and glyme while the potassium, rubidium, and cesium salts are insoluble. In the presence of air, these salts fume and are quickly discolored. They appear to be quite stable under vacuum in both the solid state and in solution, showing only minimal decomposition after 1 week, as judged from physical appearance, lack of gas evolution, infrared spectra, and boron-11 NMR spectra.

Protonation of $K_2[B_5H_9]$ or $Cs_2[B_5H_9]$ with HCl or HBr provides a convenient route to B_5H_{11} Reaction (11). Pentaborane(11) has



been obtained in yields up-to 38%. This represents the simplest, most convenient, and safest preparative method to date for B_5H_{11} .

The crown ether (dibenzo-18-crown-6) complexes of the potassium, rubidium, and cesium salts of $[B_5H_9]^{2-}$ are soluble in THF and glyme and thus could be used to obtain NMR spectra. The boron-11 NMR spectrum of $[K(\text{dibenzo-18-crown-6})_2[B_5H_9]]$ in THF is: -16.1 ppm ($J = 132$ Hz, 4 B), -51.7 ($J = 157$ Hz, 1 B) ($\delta(\text{BF}_3\text{OEt}_2) = 0.00$ ppm). The boron-11 NMR spectrum of $[B_5H_9]^{2-}$ indicates that it is highly fluxional. A two-electron reduction of nido- B_5H_9 to arachno- $[B_5H_9]^{2-}$ is expected to open the B_5H_9 square pyramid to give a boron framework like that of B_5H_{11} (a pentagonal pyramid with one basal vertex site absent) as illustrated below (Figure 6).

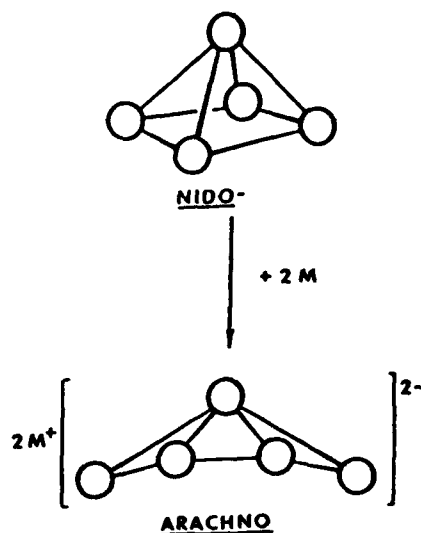


Figure 6. Expected structural change in the B_5 framework caused by two-electron reduction of nido- B_5H_9 to arachno- $[B_5H_9]^{2-}$.

The fact that only two NMR signals are observed in the ^{11}B spectrum indicates that $[\text{B}_5\text{H}_9]^{2-}$ is highly fluxional at room temperature. Low-temperature (-70°C) ^{11}B NMR spectra showed broadening of the signals; however, additional signals were not observed. Boron-11 NMR spectra of other pentaborate anions, $[\text{B}_5\text{H}_8]^-$, $[\text{B}_5\text{H}_{10}]^-$, and $[\text{B}_5\text{H}_{12}]^-$, also show two doublets in a relative ratio of 4:1.⁴⁰ Although the ^{11}B NMR spectrum of $[\text{B}_5\text{H}_9]^{2-}$ is very similar to that obtained for the $[\text{B}_5\text{H}_8]^-$ anion, the stabilities, solubilities and IR spectra of $[\text{B}_4\text{H}_9]^{2-}$ salts are very different from those of $[\text{B}_5\text{H}_8]^-$ salts. In addition, protonation of $[\text{B}_5\text{H}_9]^{2-}$ produces B_5H_{11} in good yield and no B_5H_9 is produced in this protonation. On the other hand protonation of $[\text{B}_5\text{H}_8]^-$ gives nearly quantitative yields of B_5H_9 .⁴¹

Over 30 years ago claims⁴² were made for the preparation of the $[\text{BH}(\text{CH}_3)_2]^{2-}$ dianion; however, the evidence was not strong. From the reaction of diborane with alkali metal naphthalide in THF, Reaction (12), we have prepared what appears to be the $[\text{BH}_3]^{2-}$ ion. The reaction is stoichiometric, giving a



M = Na, K, Rb, Cs

product which is stable in the absence of air and displays a very clean ^{11}B NMR spectrum, a quartet 1:3:3:1 in the range -27 to -18 ppm ($\delta(\text{BF}_3\text{OEt}_2) = 0.00$ ppm) in accord with the formulation

$[\text{BH}_3]^{2-}$. The chemical shift is a function of the cation, which probably reflects ion-pairing. In view of the stoichiometry of the reaction, the product is probably not $[\text{B}_2\text{H}_6]^{2-}$.

The $[\text{BH}_3]^{2-}$ dianion is of appreciable theoretical significance since it is the analogue of the $[\text{CH}_3]^-$ carbanion, and it might also have practical significance as a strong nucleophile. We are currently engaged in characterizing this anion, including an X-ray crystal structure determination as well as its chemistry.

We attempted to reduce $n\text{-B}_{18}\text{H}_{22}$ by alkali metal-naphthalide, using procedures described above. Instead of obtaining $[n\text{-B}_{18}\text{H}_{22}]^{2-}$ we obtained the doubly deprotonated species $[n\text{-B}_{18}\text{H}_{20}]^{2-}$, the structure of which (Figure 7) was determined

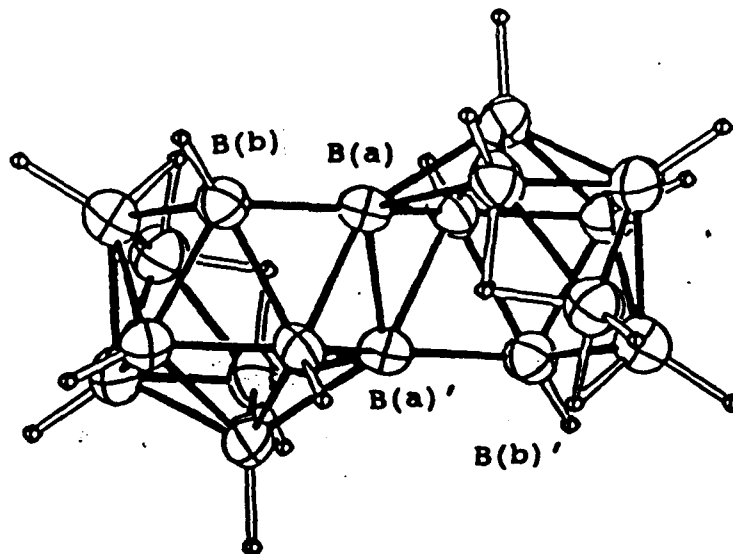
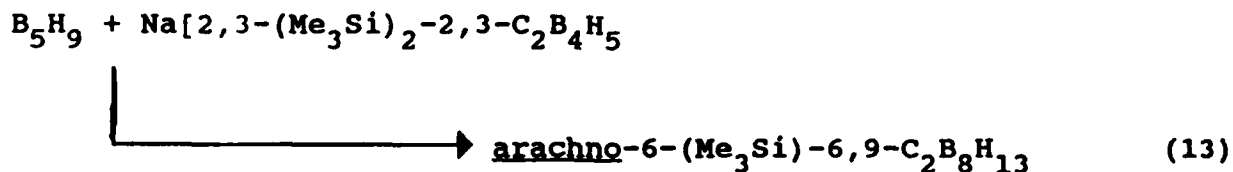


Figure 7. The molecular structure of $[n\text{-B}_{18}\text{H}_{20}]^{2-}$ (ORTEP plot with 50% thermal ellipsoids).

from an X-ray crystallographic study of $[\text{Na}(\text{THF})_3]_2[\eta\text{-B}_{18}\text{H}_{20}]$. This structure differs from that of the parent molecule in that there is no hydrogen bridge between $\text{B}(\text{a})\text{-B}(\text{b})$ and $\text{B}(\text{a}')\text{-B}(\text{b}')$ in the anion structure, while such bridges occur in the neutral parent $\eta\text{-B}_{18}\text{H}_{22}$.

VI. Formation of arachno-6-((CH_3)₃Si)-6,9- $\text{C}_2\text{B}_8\text{H}_{13}$
through a Cage-Expansion Reaction

Since our earlier work, described in Section I above showed that the reaction of $[\text{B}_5\text{H}_8]^-$ with B_5H_9 results in a cage expansion to give $[\text{B}_9\text{H}_{14}]^-$, it was of interest to determine if this type of reaction might occur between a nido-carborane anion and B_5H_9 to give an expanded carborane cage. This reaction resulted in the synthesis of a rare type of carborane, an arachno- C_2B_8 , through a cage expansion reaction,⁴³ Reaction (13). The carborane arachno-6-(Me_3Si)-6,9- $\text{C}_2\text{B}_8\text{H}_{13}$ was obtained in 21% yield. This compound is air stable. It sublimes in vacuum at 110 °C.



The molecular structure of this carborane (Figure 8) was determined from a single crystal X-ray study. Its structure is

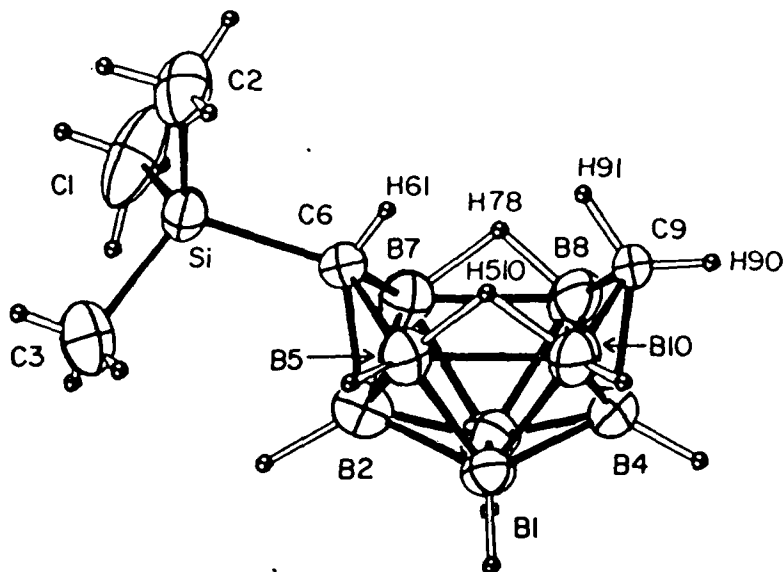


Figure 8. The molecular structure of arachno-6-(Me₃Si)-6,9-C₂B₈H₁₃ (ORTEP plot with 50% thermal ellipsoids)

similar to that of the isoelectronic arachno-[B₁₀H₁₄]²⁻ anion. Although NMR spectra are consistent with a molecule having C_s symmetry, the crystal structure shows that the cage is distorted to C₁ symmetry, apparently the result of non-bonded interaction between the Me₃Si group and the terminal hydrogen on B(2). This is the first structure determination of a 10-vertex arachno-carborane.

The boron-11 NMR spectrum of arachno-6-(Me₃Si)-6,9-C₂B₈H₁₃ was assigned on the basis of a 2D ¹¹B-¹¹B NMR study. Five ¹¹B resonances are present in the spectrum in the ratio 1:1:2:2:2.

These signals and their assignments are: 5.73 ppm (B2); 4.80 ppm (B4); -15.03 (B8, B10); -16.15 ppm (B5, B7); -35.58 ppm (B1, B3) (δ (BF3OEt2) = 0.00 ppm). Boron-11 spin-decoupling reveals five sets of terminal B-H resonances in the proton spectrum in the ratio 1:1:2:2:2 at 2.87, 2.83, 2.28, 2.26, 0.95 ppm, and a B-H-B resonance at -2.74 ppm.

VII. Boron Nitride Precursors

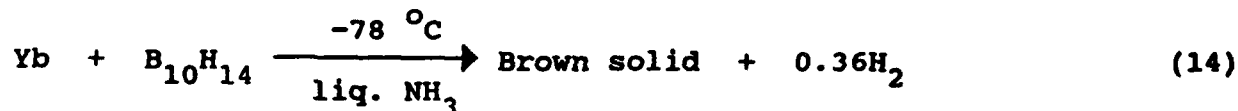
In view of the current needs for boron nitride materials as high temperature resistant coatings and structural materials, we have relatively recently turned our attention to the preparation and study of materials which might serve as possible precursors to boron nitride fibers and films. While our results are preliminary in nature, they are encouraging and we are pursuing these systems further.

Reactions with B-trichloroborazene, $\text{Cl}_3\text{B}_3\text{N}_3\text{H}_3$, and alkali metals in the presence of the electron carriers benzophenone and naphthalene have been studied. A gel-like material is formed from the reaction of $\text{Cl}_3\text{B}_3\text{N}_3\text{H}_3$ with $\text{Na}^+(\text{C}_6\text{H}_5)_2\text{CO}^-$ in ratios of 1:1-1:3. The properties of the gels formed are currently under study in a cooperative effort with Professor Eric Kreidler of the Department of Ceramic and Metallurgical Engineering.

VIII. Reduction of Decaborane(14) by the Lanthanide Metals;
Precursors to Lanthanide Borides

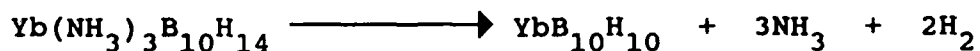
It is well known that borides of the transition metals, lanthanides, and actinides can possess a number of useful properties (catalytic behavior, desirable mechanical, magnetic, electronic, and thermal properties) which depend upon the particular combination of boron and metal. A conventional process for forming borides involves the reaction between the metal (or metal oxide) and boron (or boron carbide). In a number of cases oxidation products such as metal oxides or boron oxide contaminate the metal boride product. To obviate these problems, Japanese workers have prepared cerium and gadolinium borides from $M_2(B_{10}H_{10})_3$ ($M = Ce Gd$).⁴⁴ High quality borides are obtained as single phases by decomposing these B_{10} complexes at 1000 to 1400 °C in the presence of the metal hydride or metal in a hydrogen atmosphere which was added to adjust the metal-boron ratio to produce MB_4 or MB_6 as desired. We plan a similar approach to the formation of metal borides and have prepared lanthanide- B_{10} precursor complexes through the reduction of $B_{10}H_{14}$ by the lanthanide metals.

When we added $B_{10}H_{14}$ to an ammonia solution of Eu or Yb at -78 °C, a rapid reaction took place, Reaction (14), which was

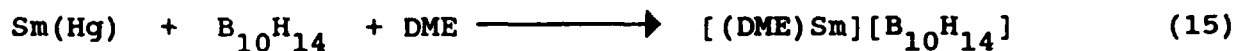


complete within 5 minutes. The brown solid is a mixture of lanthanide boranes which is insoluble in ether solvents.

Extraction with CH_3CN leaves behind solid $\text{Yb}(\text{NH}_3)_3\text{B}_{10}\text{H}_{14}$ which is transformed to $\text{YbB}_{10}\text{H}_{10}$ by heating at 180°C .



We have also reduced $\text{B}_{10}\text{H}_{14}$ using lanthanide metal amalgams. A samarium amalgam in ether in the presence of 1,2-dimethoxyethane (DME) reduced $\text{B}_{10}\text{H}_{14}$ to $[\text{B}_{10}\text{H}_{14}]^{2-}$, Reaction (15). This complex



is thermally decomposed at 185°C to form the $\text{SmB}_{10}\text{H}_{10}$ complex. While this effort is still in its early stages our results are very encouraging and we will pursue these studies further.

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List of Publications Resulting from ARO Support

- (1) Lawrence, S. H.; Shore, S. G.; Koetzle, T. F.; Huffman, J. C.; wei, C.-Y.; Bau, R. "Preparation, X-ray, and Neutron Diffraction Structure Determination of the Chlorotrihydroborate Ion, $[\text{BH}_3\text{Cl}]^-$ " Inorg. Chem. **1985**, 24, 3171.
- (2) Khan, S. I.; Chiang, M. Y.; Bau, R.; Koetzle, T. F.; Shore, S. G.; Lawrence, S. H. "A Neutron diffracton Study of $\{[(\text{C}_6\text{H}_5)_3\text{P}]_2\text{N}\}^+[\text{B}_2\text{H}_7]^- \text{CH}_2\text{Cl}_2$ at 80 °K." J. Chem. Soc. Dalton **1986**, 1753.
- (3) Lawrence, S. H.; Wermer, J. R.; Boocock, S. K.; Banks, M. A.; Keller, P. C.; Shore, S. G. "Pentaborane(9) as a Source for Higher Boron Hydride Systems. A New Synthesis of nido-5,6-(CH_3)₂-5,6- $\text{C}_2\text{B}_8\text{H}_{10}$ " Inorg. Chem. **1986**, 5, 1041.
- (4) Wermer, J. R.; Hosmane, N. S.; Alexaner, J. J.; Siriwardane, U.; Shore, S. G. "Synthesis and X-ray Crystal Structure of arachno-6-(CH_3)₃Si)-6,9- $\text{C}_2\text{B}_8\text{H}_{13}$ through a Cage-Expansion Reaction of nido-2,3-((CH_3Si)₂-2,3- $\text{C}_2\text{B}_8\text{H}_6$ " Inorg. Chem. **1986**, 25, 4351.
- (5) Wermer, J. R.; Shore, S. G. "Reduction of B_5H_9 by Alkali Metals. Preparation of the Dianion $[\text{B}_5\text{H}_9]^{2-}$ and a New Route to B_5H_{11} " Inorg. Chem. **1987**, 26, 1645.
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(9) Getman, T. D.; Shore, S. G. "Closo- $[B_{11}H_{11}AlCH_3]^{2-}$ an Aluminaborane Analogue of the closo- $B_{11}H_{12}]^{2-}$ Dianion; Synthesis, Characterization and Molecular Structure" Inorg. Chem. 1988, 27, 3439.

(10) Getman, T. D.; Krause, J. A.; Niedenzu, P. M.; Shore, S. G. " $[B_9H_{13}]^{2-}$ an arachno- $[B_nH_{n+4}]^{2-}$ Dianion; Synthesis, Characterization, and Molecular Structure," Inorg. Chem. Submitted.

List of Participating Scientific Personnel

1. Professor Sheldon G. Shore, Principal Investigator
2. Terry Brenner, undergraduate student summer research participant (Fellowship, no compensation from the grant).
2. Dr. Thomas Getman, Ph. D. March 1988, graduate student and postdoctoral associate
3. Dr. Tara Hill, postdoctoral associate
4. Mrs Zhu Hong, research assistant
5. Professor Naryan Hosmane, Visiting Professor from Southern Methodist University
6. Eric Moehr, undergraduate student summer research participant (Fellowship, no compensation from the grant).
6. Mr. Phillip Niedenzu, graduate student
7. Dr. Joseph Wermer, Ph. D. January 1987, graduate student and postdoctoral associate
8. James White, graduate student
9. Professor Guomin Zhang, Visiting Exchange Professor from Hunan University (No compensation from the grant).