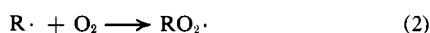


## The Stoichiometrically Controlled Reaction of Organoboranes with Oxygen under Very Mild Conditions to Achieve Essentially Quantitative Conversion into Alcohols

Sir:

The reaction of organoboranes with oxygen under very mild conditions may be controlled to give an essentially quantitative conversion of all three alkyl groups on boron to the corresponding alcohol.

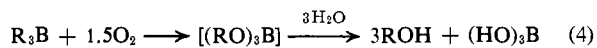
Trialkylboranes react readily with oxygen<sup>1</sup> and, consequently, must be protected under an inert atmosphere for most reactions. The autoxidation of dilute solutions of trialkylboranes has been of considerable theoretical interest.<sup>2</sup> A radical-chain process occurs with an alkyl radical being displaced from boron (eq 3).



More recently it has become apparent that such radical-chain reactions involving organoboranes may also be of synthetic interest. Thus, the slow admission of air initiates 1,4 addition of trialkylboranes to "inert"  $\alpha,\beta$ -unsaturated compounds by a radical process.<sup>3</sup> This oxygen-initiated 1,4-addition reaction has opened a new area of vast synthetic utility, now being explored.

The direct oxidation of trialkylboranes with oxygen, however, has hitherto not been of synthetic utility. Sufficient oxygen is absorbed to oxidize all three carbon-boron bonds, but the reaction is reported to be complex,<sup>4</sup> especially in tetrahydrofuran (THF) solution. Long reaction times and elevated temperatures were used for the oxidations with air in an attempt to achieve high conversion to alcohol. We undertook to study such oxidations in the hope of overcoming some of the difficulties which have been reported.<sup>4</sup> Since THF is a common solvent for hydroboration,<sup>5</sup> it would be particularly convenient if clean oxidations could be achieved with oxygen in this solvent.

Quantitative oxidation of the organoborane to the corresponding alcohol would presumably involve the uptake of 1.5 mol of oxygen/mol of organoborane, followed by hydrolysis of the intermediate boron derivative (eq 4).



We explored the oxidation of trialkylboranes in THF by adapting the automatic hydrogenator<sup>6</sup> for generating oxygen and following the reaction. Oxygen was produced by the basic manganese dioxide catalytic

(1) E. Frankland, *J. Chem. Soc.*, 15, 363 (1862); J. R. Johnson and M. G. Van Campen, *J. Amer. Chem. Soc.*, 60, 121 (1938).

(2) (a) A. G. Davies and B. P. Roberts, *J. Chem. Soc. B*, 311 (1969); (b) P. G. Allies and P. B. Brindley, *ibid.*, 1126 (1969); (c) P. J. Krusic and J. K. Kochi, *J. Amer. Chem. Soc.*, 91, 3942 (1969).

(3) H. C. Brown and G. W. Kabalka, *ibid.*, 92, 714 (1970).

(4) S. B. Mirviss, *ibid.*, 83, 3051 (1961).

(5) H. C. Brown, "Hydroboration," W. A. Benjamin, New York, N. Y., 1962.

(6) C. A. Brown and H. C. Brown, *J. Amer. Chem. Soc.*, 84, 2892 (1962). We utilized a commercial model of the hydrogenator available from Delmar Scientific Laboratories, Maywood, Ill. 60154.

decomposition of a hydrogen peroxide solution. The generator, a 200-ml flask immersed in a water bath, was charged with 3 g of manganese dioxide, 5 ml of water, and 2 ml of 3 *N* sodium hydroxide. The tubing leading from the generator was filled with glass wool and the tube to the reaction flask was filled with sodium hydroxide pellets to absorb any water. The buret was filled with a standardized<sup>7</sup> aqueous hydrogen peroxide solution. The mercury valve meters in the hydrogen peroxide solution and maintains a constant pressure as oxygen is absorbed by the organoborane solution. Consequently the reaction may be followed conveniently merely by reading the buret.

Using a 0.5 *M* tri-*n*-butylborane solution in THF at 0°, we found that the reaction with air was rapid at first, but soon became slow and failed to proceed to completion in a reasonable time. However, the use of pure oxygen produced a rapid reaction.<sup>8</sup> The rate of stirring was important. For maximum efficiency a magnetic stirrer fitted with Teflon collar was used.<sup>6</sup> Under these conditions more than the theoretical amount of oxygen (eq 4) can be absorbed and a corresponding decrease in alcohol results. Fortunately, using the present apparatus, the course of the reaction is readily followed and the reaction can be stopped at precisely 100% oxygen absorption. Treatment with aqueous alkali gives a nearly quantitative yield of alcohol.

Since the oxidation is so rapid during the initial stages, the apparatus must be carefully flushed with oxygen without significant absorption of the gas prior to the time the reaction is made to proceed by initiating rapid stirring of the mixture. This difficulty is easily overcome by flushing the apparatus with an empty flask attached in place of the usual reaction flask. This empty flask is then replaced by the reaction flask and the remaining nitrogen carefully flushed from the system in one of two ways. The first proved satisfactory for the highly reactive secondary organoboranes in small scale reactions. It consists of removing a known amount (usually 50 ml) of gas from above the THF solution with a syringe while generating oxygen at such a rate as to keep the system at atmospheric pressure. The second method, used for the less reactive primary alkylboranes or for preparative scale reactions, involves carefully and quickly flushing the system by injecting 2 ml of 30% hydrogen peroxide into the generator once the reaction flask is in place on the flushed apparatus. Stirring then initiates a rapid reaction.

The oxidation procedure was applied to a representative number of olefins. The results are summarized in Table I.

The following procedure describing the conversion of 2,4,4-trimethyl-1-pentene into 2,4,4-trimethyl-1-pent-

(7) The hydrogen peroxide solution was standardized by injecting an aliquot into the generator flask and measuring the oxygen produced in a gas buret at the exit of the apparatus.

(8) *Caution!* Neat tri-*n*-butylborane reacts explosively with pure oxygen. However, no difficulty was encountered with the usual oxidations in tetrahydrofuran solution.

**Table I.** The Controlled Reaction of Organoboranes with Oxygen to Form Alcohol

Olefin in R <sub>3</sub> B <sup>a</sup>	Time, min <sup>b</sup>	Yield, % <sup>c</sup>	Isomer <sup>d</sup>
1-Butene	5	94	95% p, 5% s
1-Octene	5	96	95% p, 5% s
Isobutene	75	98	100% p
2-Methyl-1-pentene	75	96	
2,4,4-Trimethyl-1-pentene	75	96 (88)	
2-Butene	5	95	
Cyclopentene	5	95	
Cyclohexene	6	98 (80)	
Norbornene	6	91	14% endo <sup>e</sup>
1-Methylcyclopentene	7.5	99	19% cis <sup>e</sup>

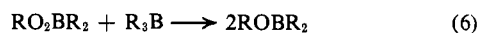
<sup>a</sup> 10 mmol of R<sub>3</sub>B. <sup>b</sup> Time for absorption of 1.5 mol of O<sub>2</sub>/mol of R<sub>3</sub>B. <sup>c</sup> By glpc (isolated yield in parentheses). <sup>d</sup> p, primary; s, secondary. <sup>e</sup> Oxidation with alkaline hydrogen peroxide gives 99.5% exo isomer and 100% trans isomer.<sup>5</sup>

anol is representative. A dry 200-ml flask equipped with a septum inlet and a magnetic stirrer with Teflon collar was flushed with nitrogen. The flask was charged with 50 ml of dry THF and 16.9 g of 2,4,4-trimethyl-1-pentene (150 mmol) and cooled to 0°. Hydroboration was achieved by the dropwise addition of 18 ml of a 2.68 M solution of borane in THF (150 mmol of hydride) at 0° followed by stirring at room temperature for 1 hr. The solution was cooled to 0° and the flask attached to the automatic oxygenator previously flushed with oxygen (inject 15 ml of 30% hydrogen peroxide into generator with an empty 100-ml flask in place of the reaction flask). The system was further flushed by injecting 2 ml of 30% hydrogen peroxide once the flask was in place. The stirrer was started and oxygen absorption (with the flask immersed in an ice bath) was followed by reading the buret filled with freshly standardized 30% hydrogen peroxide (a more dilute solution, 3%, was used for glpc reactions on a 10-mmol scale). After the theoretical absorption of oxygen, the flask was removed and 18 ml of 3 N sodium hydroxide added dropwise at 0° (exothermic reaction). The solution was stirred for 5 min, the aqueous layer was saturated (K<sub>2</sub>CO<sub>3</sub>), separated, and washed with diethyl ether, and the combined extracts were dried (K<sub>2</sub>CO<sub>3</sub>). Distillation gave 17.2 g (88%) of 2,4,4-trimethyl-1-pentanol, bp 169–170°, n<sub>D</sub><sup>20</sup> 1.4263.

The controlled oxidation of organoboranes is a very clean reaction. Only minor amounts of carbonyl and hydrocarbon products were detected. All organoboranes reacted quite rapidly in the initial stages, but varied considerably in the time required to achieve the desired uptake of oxygen (1.5 mol of O<sub>2</sub>/mol of R<sub>3</sub>B). The reaction involving organoboranes containing secondary alkyl groups, such as tri-*sec*-butylborane, proved exceptionally fast, but could be made to proceed at a convenient rate by not displacing all of the nitrogen atmosphere. The reactions involving straight-chain primary groups, such as tri-*n*-butylborane, are slower, but even so are complete in approximately 5 min. On the other hand, organoboranes containing primary alkyl groups with a β-methyl substituent are considerably slower, the quantitative uptake of oxygen requiring 75 min for triisobutylborane and similar derivatives. We account for the essentially quantitative yields realized on the basis that the mild reaction

conditions used avoid decomposition of intermediate peroxides.

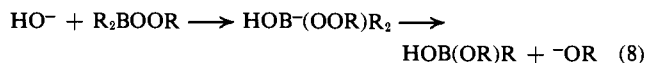
The first carbon–boron bond is oxidized very rapidly by a radical-chain process (eq 1–3).<sup>2a</sup> This initial oxidation produces a peroxide, which may either react with a second mole of oxygen (eq 5) or may undergo an intermolecular redox reaction<sup>9</sup> (eq 6). The borinate



ester produced may then react with oxygen (eq 7). In



any event, irrespective of the precise components present in the reaction mixture, addition of sodium hydroxide then causes the remaining carbon–boron bonds to be oxidized by the remaining peroxide linkage. This may involve either a rearrangement with displacement of the alkyl group from boron to oxygen<sup>10</sup> (eq 8), or by



hydrolysis of the alkyl peroxide followed by base-catalyzed oxidation, as with hydrogen peroxide,<sup>5</sup> of the carbon–boron bond by the peroxide anion.

In contrast to oxidation by alkaline hydrogen peroxide, a portion of the present reaction proceeds through alkyl radicals (eq 1). This results in some loss of the stereospecificity of the hydroboration reaction, as reported for norbornene and 1-methylcyclopentene (Table I).

These results reveal that the reaction of organoboranes with oxygen may be controlled under remarkably mild conditions to give nearly quantitative conversion to alcohol. The discovery that organoboranes may undergo such clean free-radical reactions, readily controlled for preparative requirements, opens a new area of synthetic and theoretical interest. We are continuing to explore this area.

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(10) M. H. Abraham and A. G. Davies, *J. Chem. Soc.*, 429 (1959).

(11) National Science Foundation Predoctoral Fellow.

(12) Postdoctorate research associate on Grant No. 10937 from the National Institutes of Health.

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### The Light-Induced Reaction of Bromine with Trialkylboranes in the Presence of Water. A Remarkably Simple Procedure for the Union of Two or Three Alkyl Groups to Produce Highly Substituted Alcohols

Sir:

Trialkylboranes undergo a rapid reaction with bromine in the presence of light to produce the corresponding α-bromoorganoboranes and hydrogen bromide. If water is present, the hydrogen bromide is absorbed and protonolysis of the α-bromo intermediate<sup>1</sup> is avoided. Instead, a facile rearrangement of alkyl groups from boron to carbon occurs (eq 1, 2).

(1) C. F. Lane and H. C. Brown, *J. Amer. Chem. Soc.*, **92**, 7212 (1970).