

Synthetically Useful Reactions with Metal Boride and Aluminide Catalysts

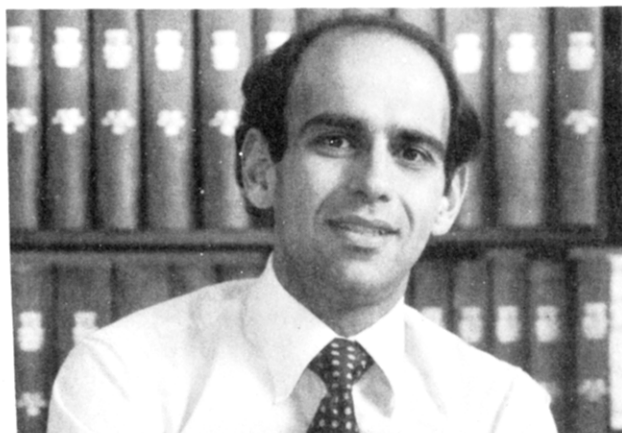
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Bruce Ganem was born in Boston, MA, in 1948 and attended Harvard College. After graduate study with Gilbert Stork at Columbia University and a National Institutes of Health postdoctoral fellowship with W. S. Johnson at Stanford, he joined the Cornell faculty in 1974 where he became Professor of Chemistry in 1980. Dr. Ganem's early scientific interests in natural products synthesis, synthetic methodology, and bioorganic chemistry have led recently to new interdisciplinary forays into biochemistry, enzymology, and immunology. Current interests include studies on the shikimic acid biosynthetic pathway, the mechanism and function of carbohydrate-processing enzymes, new chemistry of naturally occurring polyamines, and the design and assembly of well-characterized synthetic vaccines.



John O. Osby was born in Denver, CO, in 1958. He received his B.A. degree in Chemistry in 1980 from The Johns Hopkins University. After a one-year industrial position in inorganic analytical chemistry, he entered Cornell University where he joined Professor Bruce Ganem's research group. Dr. Osby's graduate work focused on the mechanism of cobalt(II)- and nickel(II)-promoted sodium borohydride and lithium aluminum hydride reductions. He received his Ph.D. degree in 1985, and has since joined the Dow Chemical Company as a research chemist in Midland, Michigan.

I. Introduction

A. Background

Since the pioneering discovery of nickel-catalyzed hydrogenation by Paul Sabatier, for which he won the Nobel Prize in 1912, organic chemists have been fascinated with transition metals and their compounds as promoters for other synthetically important reductions. In the past 40 years, metal hydrides, particularly sodium borohydride and lithium aluminum hydride, have emerged as preeminent reducing agents in modern organic chemistry.^{1,2} These are extraordinarily versatile

reagents capable of reducing most functional groups. Moreover by attaching organic ligands at boron or aluminum or changing the metal counterion, one can modulate the scope, regio-, and stereoselectivity of such

reductions. Literally hundreds of substituted boron and aluminum hydrides have been described in the chemical literature and dozens are now commercially available.^{3,4}

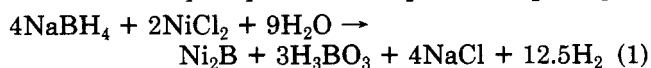
More recently, transition metal salts have been used as catalysts or additives in conjunction with NaBH₄ and LiAlH₄ to modify or enhance the properties of these reagents. Nearly every conceivable combination of salt and hydride has been investigated with the concomitant development of many useful new synthetic methods.⁵ The resulting systems are complex, however, and in most cases virtually nothing is known about mechanism or reactive intermediates. Boron and aluminum hydrides may combine with metal halides in several different ways: (1) simple metathesis (e.g., LiCl + NaBH₄, LiBH₄ + NaCl),⁶ (2) reduction of the metal halide to the metal,⁷ (3) conversion of metal halide to metal hydride,⁸ (4) some combination of (2) and (3), viz., FeCl₃ + LiBH₄ → Fe(BH₄)₂,⁹ or (5) formation of a boride¹⁰ or aluminide.¹¹ Furthermore, it is often unclear whether the metal salt serves a true catalytic function or whether some transient, metalloidal complex formed in situ is the actual reducing agent. Recently we had occasion to probe the mechanism of several transition-metal-assisted hydride reductions which are of particular interest to synthetic organic chemists.¹²⁻¹⁴ The unambiguous involvement of metal borides and aluminides in case after case we studied prompted us to organize the present review.

B. Catalyst Preparation

1. Borides

Historically, borides were first produced by the combination of boron with metallic or metalloidal elements less electronegative than itself. For the most part, borides are very hard, high-melting, refractory substances whose structures and stoichiometries do not conform to the ordinary concepts of valence. Borides with low boron-to-metal ratios (M₄B, M₃B, M₂B) contain isolated boron atoms, however as the proportion of boron increases (M₃B₂, M₄B₃, M₃B₄), borides with single and double chains of borons appear. Borides with formulae like MB₄, MB₆, and MB₁₂ exist in three-dimensional arrays with open networks of boron atoms interpenetrating a regular metal atom lattice.^{15,16}

The industrial synthesis of borides usually involves (1) reduction of metal oxides using a mixture of boron carbide and carbon, (2) electrolysis, or (3) direct reaction of the elements. Some borides prepared in this fashion possess good electrical and thermal conductivity properties while others show promise as high-temperature semiconductors. A much simpler synthesis was discovered by H. I. Schlessinger in his pioneering work on borohydrides.¹⁰ Combinations of cobalt or nickel (or other metal salts) with aqueous NaBH₄ deposit finely divided black precipitates of Co₂B and Ni₂B (eq 1).



Because they actively catalyzed the decomposition of borohydride,¹⁰ these borides have been commonly used as a practical, controlled source of hydrogen (eq 2).



Other versions of this synthesis have been conducted in alcoholic or ether solvents, under an inert atmosphere

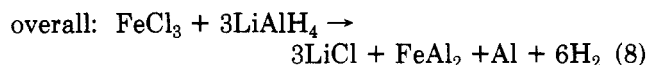
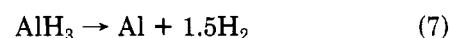
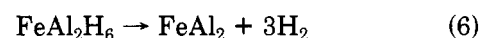
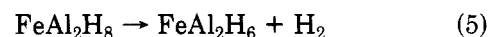
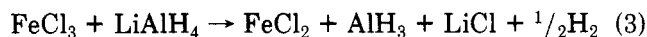
TABLE I. NaBH₄ Reduction of Transition-Metal Cations

metal	element	boride	metal	element	boride
Fe(III)	Fe(0)	Fe(B)	Pd(II)	Pd(0)	Pd(B)
Co(II)		Co ₂ B	Ag(I)	Ag(0)	
Ni(II)		Ni ₂ B	Os(VIII)	Os(0)	Os(B)
Cu(II)	Cu(0)	Cu(B)	Ir(IV)	Ir(0)	Ir(B)
Ru(III)	Ru(0)	Ru(B)	Pt(II)	Pt(0)	Pt(B)
Rh(III)	Rh(0)	Rh(B)			

like nitrogen, or under hydrogen pressure.¹⁷ Borides have been deposited in the presence of a second (promoter) metal,¹⁸ on inert solid supports,¹⁹ or as colloidal suspensions on solvent-swollen polymers.²⁰ As will be seen, small variations in the method of preparation can dramatically affect the activity, selectivity, physical, and chemical properties of the boride.²¹ Cobalt(II), nickel(II), and copper(II) salts uniformly produce borides when treated with NaBH₄ in protic solvents. Iron(III), ruthenium(III), rhodium(III), palladium(II), osmium(VIII), iridium(IV), and platinum(IV) salts afford black precipitates which catalyze NaBH₄ decomposition. They may be borides, zerovalent metals, or a mixture (see Table I).^{5,22}

2. Aluminides

The first aluminides of iron and cobalt were reported 30 years ago by Schaeffer and Stewart.^{9,11} Reaction of CoBr₂ with LiAlH₄ in ether gave two mol of hydrogen and a black, pyrophoric precipitate of CoAl₂. Likewise LiAlH₄ reacted with FeCl₃ to give as the ultimate products aluminum, FeAl₂, LiCl, and H₂ (eq 8). A series of five discrete processes was proposed to account for the overall stoichiometry in the latter process (eq 3-7).



C. Catalyst Composition and Properties

1. Borides

The actual composition of borides prepared from inorganic salts depends to a great extent on the specific mode of preparation. Maybury, Mitchell, and Hawthorne analyzed nickel and cobalt borides prepared in ethanol under N₂ using excess NaBH₄ and concluded that the stoichiometries Ni₂B and Co₂B inadequately represented their constitution. Besides containing solvent and adsorbed hydrogen, which was released upon heating, the solids were contaminated with tightly trapped NaCl. Freshly precipitated cobalt boride in water slowly liberated hydrogen with formation of boric acid. On the basis of the metal:boron ratio and the amounts of H₂ evolved, the formulae (Ni₂B)₂H₃ and (Co₂B)₅H₃ were suggested.²³

The effect of solvent on boride activity and selectivity was first demonstrated by C. A. Brown and H. C. Brown

who prepared a series of hydrogenation catalysts by the reaction of NaBH_4 with $\text{Ni}(\text{OAc})_2$. "P-1" nickel boride prepared in water was considerably more active than Raney nickel and exhibited a markedly lower tendency to isomerize olefins. "P-2" nickel boride prepared in ethanol could selectively hydrogenate olefins and dienes of different substitution patterns, and converted alkynes stereoselectively into *cis*-alkenes.²⁴ The *cis*-*trans* selectivity achieved with P-2 boride could further be improved by the addition of catalyst modifiers such as ethylenediamine.²⁵

Most borides of interest have been prepared in protic solvents and are stable to air. However the reaction of CoBr_2 with LiBH_4 in anhydrous ether formed a greyish-white solid at low temperature, presumed by analogy with other systems to be a cobalt borohydride. Upon warming to room temperature, the solid darkened and hydrogen evolution commenced. Ultimately a black, pyrophoric precipitate of CoB_2 remained which reacted with methanol to form $(\text{CH}_3\text{O})_3\text{B}$ along with elemental cobalt and hydrogen.¹¹ To our knowledge, the catalytic properties of this potentially very active boride have not been explored.

Many borides prepared in alcohol or water can be filtered and stored moist without problem. However when dry, they become pyrophoric.²³ They are insoluble in base but hydrolyze readily in acid with vigorous H_2 evolution. X-ray diffraction analysis reveals their structures to be amorphous.^{26,27} Certain preparations of nickel boride, however, become crystalline when heated to 250 °C or higher. These crystalline materials have been identified as mixtures of Ni and Ni_2B or Ni_3B . While loss of boron with concomitant crystallization of the structure has been confirmed by several groups,²¹ it remains to be seen whether these more ordered borides retain their former activity.

Recently Okamoto et al. have used X-ray photoelectron spectroscopy to examine the surface structure of amorphous nickel boride and nickel phosphide catalysts.²⁸⁻³⁰ Studies of the former revealed that surface nickel existed in three forms: Ni(0), nickel oxide (NiO), and boron-bound nickel. Two forms of boron were detected, regardless of the solvent or metal salt used: nickel-bound boron (designated B-I boron) and BO_2^- (designated B-II boron). Analogous components were observed for cobalt boride.

Why does catalyst activity vary so markedly with the method of boride preparation? In the first place, surface contamination by spectator ions such as Na^+ and Cl^- can dramatically reduce activity. The lower the ion's solubility in the boride-forming solvent, the higher its concentration as a surface contaminant. Secondly, two lines of evidence suggest that maximizing boron-bound nickel is the key to preparing active catalysts.²⁸ (1) Catalytic activity (in hydrogenation reactions) decreases with increasing nickel oxide content, which in turn depends strongly on the starting nickel salt. For example, boride made from nickel chloride contains 17% nickel oxide and is a good catalyst, whereas that from nickel formate contains 85% nickel oxide and is only very weakly active in alkene hydrogenations. (2) The surface concentration of B-I boron (boron-bound nickel) is heavily dependent on the choice of solvent and metal salt. While the boron 1s binding energy for B-I boron in each catalyst remains constant (independent

TABLE II. Surface Characterization of Metal Borides

catalyst	precursor	metal % ^a	B/M ratio ^b	% B-I	% B-II	B-H/M ^c
Ni_2B	$\text{Ni}(\text{OAc})_2$	61	0.54	51	49	0.45
	NiSO_4	86	0.55	58	42	0.37
	NiCl_2	83	0.47	56	44	0.32
	NiBr_2	77	0.38	56	44	0.27
	$\text{Ni}(\text{HCO}_2)_2$	ca. 15				
Co_2B	$\text{Ni}(\text{NO}_3)_2$	ca. 0				
	CoSO_4	83	0.37	56	44	0.25
	CoCl_2	83	0.38	51	49	0.24
	$\text{Co}(\text{HCO}_2)_2$	81	0.39	48	52	0.23
	CoBr_2	85	0.25	53	47	0.17
FeB	$\text{Co}(\text{OAc})_2$	ca. 10				
	FeCl_2	81	0.29	22	78	0.08
PdB	PdCl_2	94	0.02	67	13 ^d	0.01
PtB	H_2PtCl_6	83	0.01	27	13 ^d	<0.01

^aFraction of metal in total surface metal. ^bTotal boron:total metal in surface. ^cFraction of boron bonded to metal. ^dRemainder is hydrogen.

of the precursor salt, reaction temperature and amounts of NaBH_4), the specific activity of catalysts increases linearly with B-I boron content. This correlation best explains, for example, why P-1 nickel boride is a more active hydrogenation catalyst than P-2 nickel boride, since the former contains 40% higher levels of B-I boron than the latter. Okamoto et al. conclude that boron bound to nickel (B-I boron) donates electrons to the nickel, resulting in electron-rich sites on the catalyst. The electron-withdrawing effect of phosphorous creates the opposite trend in nickel phosphides. Table II summarizes the surface features of some common borides prepared by reducing metal salts in water.²⁸ It provides valuable insight to the experimentalist wishing to produce a catalyst possessing specific, well-defined characteristics.

2. Aluminides

Little is known about the surface structure of transition metal aluminides. Cobalt aluminide prepared from CoBr_2 and LiAlH_4 (see section B.2) has recently been analyzed by argon plasma emission spectroscopy and assigned the empirical formula $\text{CoAl}_{1.6}$. However this composition was markedly dependent on the reaction solvent (THF or ether), the specific cobalt(II) salt employed, and even the manner and rate of mixing.¹⁴ Combining solid CoBr_2 with diethyl ether solutions of LiAlH_4 led to precipitates with high average aluminum content, whereas mixing homogeneous THF solutions of CoCl_2 and LiAlH_4 resulted in finely divided cobalt aluminide with the lowest aluminum content ($\text{CoAl}_{1.1}$). Judging from trends in nickel borides and phosphides, the higher electron density on aluminum should result in even greater electron donation to metals in the corresponding aluminides. We are actively exploring new uses of NiAl_x .

D. Useful Reducing Systems

Most of the methods described in this review involve the use of sodium borohydride with borohydride-reduced catalysts. This reducing agent is a colorless, crystalline, high-melting solid which is soluble in water, alcohols, liquid ammonia, ethers, dimethyl sulfoxide, and many other common solvents.^{3a} Besides being relatively inexpensive, it is not shock or oxygen sensi-

tive, making it an ideal reagent for use even on an industrial scale.³¹

The combination of NaBH_4 with an appropriate metal salt will generally form a black precipitate of the corresponding boride in water or alcohols. However in the presence of complexing ligands,³² or in good donor solvents like *N,N*-dimethylformamide or *N,N*-dimethylacetamide,³³⁻³⁵ soluble metal (hydride, borohydride?) species are produced which can catalyze homogeneous hydrogenations or other hydride reductions. The catalytic activity of these species has been reviewed elsewhere.³⁶ **Caution:** *Concentrated solutions of NaBH_4 in DMF in the absence of reducible substrate are unsafe at elevated temperatures. Violent exothermic reactions can occur, generating flammable gases. Dissolving NaBH_4 in DMF on a large scale with inefficient cooling is hazardous. To avoid a potential violent reaction, the use of *N,N*-dimethylacetamide is recommended, especially in processes being conducted at elevated temperature.* This is not to say, however, that borides cannot be prepared in one solvent and then used to catalyze reactions in another. Very little work (besides our own recent effort)¹⁴ has been reported in this area, but more can be expected now that the essential catalytic role of borides has been demonstrated.

Cobalt and nickel borides containing promoter metals such as chromium, molybdenum, tungsten, vanadium, manganese, or rhodium have been synthesized by coreduction of the cobalt or nickel salt with chromium sulfate, sodium molybdate, sodium tungstate, ammonium vanadate, manganese chloride, or rhodium chloride. Analysis of the resulting black precipitates reveals about 2% by weight of promoter. Interestingly, NaBH_4 will not reduce any of these promoter salts (except for rhodium) in the absence of Co(II) or Ni(II).^{18,21}

Teranishi et al. have prepared cobalt-nickel binary boride catalysts by reducing equimolar mixtures of $\text{Co}(\text{Ac})_2$ and $\text{Ni}(\text{OAc})_2$ with NaBH_4 in water. Such hybrid borides displayed enhanced catalytic hydrogenation activity but selectivity proved superior using cobalt boride containing traces of promoter metals.³⁷

For the most part, metal-assisted NaBH_4 reductions are carried out using a stoichiometric quantity (sometimes greater) of the metal salt together with excess (2-10 mol equiv) of NaBH_4 . We have now shown that in many instances reactions can be conducted satisfactorily using much less metal. Since the boride is deposited in situ with concomitant H_2 evolution, good stirring of the heterogeneous system is essential.

II. Reactions Involving Borides and Aluminides

A. Hydrogenation of Alkenes and Alkynes

Many combinations of a transition metal salt with NaBH_4 or LiAlH_4 promote the reduction of unsaturated compounds, though not all involve borides or aluminides.^{5,21} In some cases, premade metal catalysts are used under an atmosphere of hydrogen, while in others the direct reduction of unsaturated compounds by " $\text{MX}_2\text{-NaBH}_4$ " is reported without mentioning whether black precipitates form or hydrogen is evolved—observations which might shed light on questions of mechanism. Borides of nickel, cobalt, palladium, and rhodium along with aluminides of cobalt, nickel, and iron have seen the most widespread use.

1. Borides

The use of nickel boride prepared from $\text{MX}_2/\text{NaNH}_4$ as heterogeneous hydrogenation catalysts was first reported by Paul et al.¹⁸ These catalysts, together with their "promoted" analogues doped with chromium, molybdenum, tungsten, vanadium, or manganese, formed finely divided black precipitates which when dried under nitrogen were neither pyrophoric nor ferromagnetic. While unpromoted nickel boride was about as active as Raney nickel in the hydrogenation of safrole, furfural, and benzonitrile, it exhibited superior catalyst life. Nickel boride could also selectively hydrogenate alkenes in the presence of ketones, alcohols, and ethers with no detectable hydrogenolysis.³⁸ Promoted nickel boride was even more active than Raney nickel in most hydrogenations.

Koritala and Dutton prepared Ni_2B by reducing nickel acetate with aqueous NaBH_4 under N_2 to produce commercially useful catalysts.³⁹ In the selective hydrogenation of soybean oil, this boride produced 80-90% mono- or diunsaturated esters and virtually no stearic acid.

In dimethylformamide (DMF) or dimethylacetamide, reduction of CoCl_2 or NiCl_2 with NaBH_4 produced dark brown/black solutions which comprised quite efficient systems for alkene hydrogenation.³³ Suspected to be cluster compounds, the active species are borderline homogeneous/heterogeneous catalysts. Rigorous exclusion of air apparently precluded boride formation in DMF.

In the systematic study of olefin heterogeneous hydrogenation using nickel boride noted earlier,^{24,25} C. A. Brown and H. C. Brown observed that P-1 nickel boride (under H_2 in ethanol, room temperature, 1 atm) was considerably more reactive than commercially Raney nickel towards less reactive alkenes like cyclopentene, cyclohexene, and cyclooctene. The P-1 boride was much less likely to isomerize reactive alkenes, and permitted the selective hydrogenation of unconjugated dienes.^{24a} Thus 2-methyl-1,5-hexadiene gave pure 2-methyl-1-hexene in 93% yield while 4-vinylcyclohexene afforded ethylcyclohex-3-ene in 99% yield.

When nickel acetate was reduced with NaBH_4 in ethanol, the activity of the resulting P-2 nickel boride proved very sensitive to steric hindrance and olefin substitution pattern (Table III). Strained double bonds were readily reduced. Little or no hydrogenolysis of benzylic, allylic, or propargylic compounds was observed, and the partial reduction of dienes and terminal alkynes to monoenes was easily achieved (Table IV). Moreover when P-2 nickel boride was used in conjunction with ethylenediamine, it selectively reduced disubstituted alkynes to *cis*-alkenes in high yield (Table V).²⁵

The reduction of diphenylacetylene and methyl hex-3-ynoate to the corresponding *cis*-alkenes has also been accomplished using $\text{NaBH}_4/\text{PdCl}_2$ in a mixture of polyethylene glycol and CH_2Cl_2 .⁴⁰ As regards mechanism, the authors noted that "the PdCl_2 apparently dissolved completely...but it is not clear whether or not Pd-black [or boride] was generated."

Recently two publications describing the direct reduction of alkenes by $\text{NaBH}_4\text{-CoCl}_2$ in protic or aprotic solvents appeared. In 1979 Chung reported that alcoholic $\text{NaBH}_4\text{-CoCl}_2$ could selectively reduce alkynes as

TABLE III. Hydrogenation of Representative Substrates over 5.0 Mmol of P-2 Ni^a

compd	initial rate, ^b mmol/min	T _{50%} , ^c min
1-octene	5.3	4.3
3-methyl-1-butene	2.0	10
3,3-dimethyl-1-butene	0.53	48
2-methyl-1-pentene	0.13	720
2-methyl-2-pentene	0.01*	>24 h
2,3-dimethyl-2-butene	0	∞
cis-2-pentene	0.31	120
trans-2-pentene	0.08*	>8 h
cyclopentene	0.6	8.0
cyclohexene	0.08*	>8 h
cycloheptene	2.1	13
cyclooctene	0.67	40
norbornene	5.6	3.4 ^e
α-methylstyrene ^d	0.25	120
benzene	0	∞

^a 40.0 mmol of substrate, 0.8 min, 95% ethanol at 25 °C, 730-mm pressure. ^b Average from 0.0 to 0.2 H₂. * denotes values measured between 0.0 and 0.05 or 0.1 H₂. ^c Time for uptake of 20.0 mmol of H₂. ^d No reduction of aromatic ring. ^e May reflect slight amount of diffusion limitation.

well as mono- and disubstituted alkenes in the presence of more highly substituted olefins.⁴¹ The selective monohydrogenation of limonene was described (see Table VI). No mechanism was proposed, but a cobalt hydride species was invoked as the active reducing agent. In 1984 Satyanarayana and Periasamy reported the solvent dependency of this reduction and contended that reaction of NaBH₄ with CoCl₂ produced either "CoH₂" (in THF:CH₃OH) or "BH₃" (in THF). Selective hydrogenation of mono- and disubstituted alkenes in CH₃OH (Table VII) was ascribed to the former species.⁴²

Earlier this year Osby et al. demonstrated that the selective hydrogenation of limonene with ethanolic CoCl₂/NaBH₄ could equally well be achieved under heterogeneous conditions using preformed Co₂B and H₂ gas.¹⁴ The boride alone (1 equiv) was incapable of reducing limonene. Homogeneous hydrocobaltation may be considered unlikely since CoCl₂ formed Co₂B so rapidly that "CoH₂" species would have been fleeting intermediates at best. Nucleophilic attack by NaBH₄ on a homogeneous alkene-cobalt complex also seemed improbable for the same reasons. While NaBH₄ might conceivably attack a heterogeneous alkene-Co₂B complex, the fact that limonene could not be reduced over Co₂B using NaBH₄ or LiBH₄ in either THF or 12:1 THF:CH₃OH (where H₂ evolution is suppressed) rendered this a remote possibility. Thus it would appear, in the two systems reported,^{41,42} that NaBH₄ functioned solely as a source of H₂ via decomposition over Co₂B.

Russell, Hoy, and Cornelius have surveyed the hydrogenation of nitrogen- and oxygen-containing unsaturated compounds over nickel boride [premade from Ni(OAc)₂ and NaBH₄ in ethanol or water and then filtered]. Unsaturated amines, amides, ethers, esters, aldehydes, ketones, alcohols, and diols all gave high yields of single compounds resulting from alkene reduction. No hydrogenolysis products were detected by gas chromatography. Only *trans*-cinnamic acid, 1,2-epoxybutane and 2-methyl-1,2-epoxypropane failed to be reduced and controls showed they were not catalyst poisons. Unsaturated nitriles have hydrogenated to saturated primary amines.⁴³

TABLE IV. Selective Hydrogenations over P-2 Nickel

compd ^a	product (%)
1-hexyne	<i>n</i> -hexane (16) 1-hexene (68) 1-hexyne (16)
3-hexyne	<i>n</i> -hexane (1) <i>cis</i> -3-hexene (96) <i>tert</i> -3-hexene (3) 3-hexyne (0)
1-octene + 2-methyl-1-pentene	<i>n</i> -octane (48) 1-octene (2) 2-methylpentane (3) 2-methyl-1-pentene (47)
1-octene + cyclohexene	<i>n</i> -octane (49) 1-octene (1) cyclohexane (2) cyclohexene (48)
norbornene + cyclopentene	norbornane (47) norbornene (3) cyclopentane (2) cyclopentene (48)
2-methyl-1,5-hexadiene	2-methylhexane (2) 2-methyl-1-hexene (96) other methylhexenes (2) 2-methyl-1,5-hexadiene (0)
4-vinylcyclohexene	ethylcyclohexane (2) 4-ethylcyclohexene (97) vinylcyclohexane (1) 4-vinylcyclohexene (0)
isoprene	2-methylbutene (4) methylbutenes (91) isoprene (5)
1,3-cyclohexadiene ^b	cyclohexane (2) cyclohexene (89) 1,3-cyclohexadiene (0) benzene (9)
5-methylenenorbornene	methylnorbornanes (1) methylnorbornenes (2) 2-methylenenorbornane (96) 5-methylenenorbornene (1)
<i>endo</i> -dicyclopentadiene (2)	tricyclodecane (2) dihydro (3) (>97) other dihydro (<1) dicyclopentadiene (0)
1-penten-3-ol ^c	<i>n</i> -pentane (0) 3-pentanol (100%)
1-vinylcyclohexanol ^c	ethylcyclohexane (0) 1-ethylcyclohexanol (100)
3-methyl-1-pentyn-3-ol ^d	3-methylpentane (0) 3-methyl-3-pentanol (100)
1-ethynylcyclohexanol ^d	ethylcyclohexane (0) 1-ethylcyclohexanol (100)

^a Hydrogenation of 40.0 mmol of substrate (40.0 mmol of each in mixtures) over 5.0 mmol of P-2 nickel in 95% ethanol at 25 °C, 1 atm; 40 ± 0.8 mmol of hydrogen used. ^b 32.0 mmol of hydrogen. ^c Hydrogen uptake 40.0 mmol. ^d Hydrogen uptake 80.0 mmol.

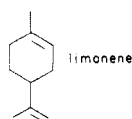
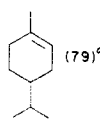
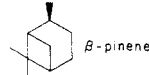
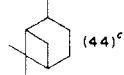
TABLE V. Stereospecific Reduction of R¹C≡CR² by P-2 Ni-eda^a

substrate (mmol)	P-2Ni, mmol	% olefin ^b	<i>cis:trans</i> ^b	total yield, (%)
hex-3-yne (40)	5.0	98	97:1	>95 ^b
hex-3-yne (200)	10.0	97	ca. 200:1	>95 ^b (80) ^c
1-phenylpropyne (100)	5.0	96	ca. 200:1	>95 ^b
hex-3-yn-1-ol (40)	5.0	98	>100:1	94 ^c

^a Amine used was 2-3 × molar amounts of catalyst. There is no evidence that this excess is required. ^b GLC analysis. ^c Isolated yield.

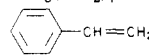
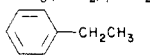
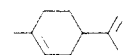
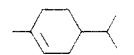
Catalytic quantities (0.1–0.25 equiv) of nickel, cobaltous, cupric, and palladium(II) salts with NaBH₄ also reduced methyl cinnamate to methyl hydrocinnamate,⁴⁴ and carda-16,20(22)-dienolide to card-17(20)-enolides.⁴⁵ Selective reduction of an alkene by NaBH₄ in the

TABLE VI. Reduction of Alkenes and Alkynes by NaBH₄ and Co(II)^a

entry	substrate	product, % yield	mol ratios of substrate/Co(II)/NaBH ₄	reacn time, h	T _{1/2}
1	styrene	ethylbenzene (>98) ^b	1/1/2	3.5	<10 min
2	1-octene	<i>n</i> -octane (>98) ^{b,d}	1/1/2	3	<10 min
3	1-dodecene	<i>n</i> -dodecane (95) ^{c,d}	1/1/2	3	
4	norbornene	norbornane (>98) ^b	1/1/2	3	
5	norbornadiene	norbornane (>98) ^b	1/1/2	2.5	
6	cyclohexene	cyclohexane (>98) ^b	1/1/2	20	~2 h
7	<i>cis</i> -stilbene	1,2-diphenylethane (>98) ^b	1/1/2.5	16	<2 h
8	<i>trans</i> -stilbene	1,2-diphenylethane (45) ^b	1/1/2.5	16	~20 h
9	 limonene	 (79) ^c	1/0.5/1	12.5	~6 h
10	 β-pinene	 (44) ^c	1/0.5/1	20	
11	1-methylcyclohexene	no reaction	1/1/3	19	
12	α-pinene	no reaction	1/1/2	24	
13	cholesterol	no reaction	1/1/2	23	
14	cholesteryl acetate	no reaction	1/1/2	24	
15	lanosterol	no reaction	1/1/2	24	
16	1-octyne	<i>n</i> -octane (>98) ^b	1/0.1/1	3	
17	1-octyne	1-octene (>95) ^b		3	
		<i>n</i> -octane (trace)	1/0.1/0.5		
		1-octyne (trace)			
18	1,2-diphenylacetylene	<i>cis</i> -stilbene (30) ^{b,c} <i>trans</i> -stilbene (10) 1,2-diphenylethane (10) 1,2-diphenylacetylene (50)	1/0.1/0.5	11	
19	cyclohexanone	cyclohexanone (~30) cyclohexanol (~70)	1/1/2	10	

^a All the reactions were run in EtOH (see text). ^b Determined by VPC. ^c Determined by NMR. ^d CoCl₂·6H₂O and anhydrous CoBr₂ could be used interchangeably.

TABLE VII. Hydrogenation of Alkenes with NaBH₄/CH₃OH-CoCl₂ in THF^a

alkene	reacn time, h ^b	product ^c	yield, ^d %
CH ₃ (CH ₂) ₇ CH=CH ₂	3	CH ₃ (CH ₂) ₇ CH ₂ CH ₃	80
 -CH=CH ₂	3	 -CH ₂ CH ₃	65
(<i>E</i>) CH ₃ (CH ₂) ₂	8	CH ₃ (CH ₂) ₆ CH ₃	70
α-pinene	12	no reaction	
cholesterol	12	no reaction	
	8		75

^a The reactions were carried out using 10 mmol of CoCl₂, 20 mmol of NaBH₄, 60 mmol of CH₃OH and 20 mmol of alkene in THF (40 mL). ^b Time taken after the addition of the alkene into the mixture containing NaBH₄-CH₃OH-CoCl₂ in THF. ^c The products were identified by spectral data (IR ¹H NMR and ¹³C NMR) and comparison with the data reported in the literature. ^d Yields are of the isolated and distilled products.

presence of a ketone carbonyl would be unusual. In fact, β-sulfenylated α,β-unsaturated ketones were reduced by using CoCl₂ or NiCl₂/NaBH₄/CH₃OH to give the corresponding saturated, desulfurized ketones in excellent yield.⁴⁶ However β-dialkylamino-α,β-unsaturated ketones, normally resistant to NaBH₄, afforded the corresponding saturated γ-amino alcohols in high yield with FeCl₃/NaBH₄/CH₃OH. The authors noted the reddish brown color at the start (FeCl₃-enamino-ketone complexes) became pale green, but no precipitate of the boride appeared. Nickel and cobalt salts were not as effective.⁴⁷ It would be interesting to compare these results with reductions using premade borides.

2. Aluminides

In 1965, Takegami et al. reported systematic studies on the hydrogenation of olefins using various mixtures of FeCl₃/LiAlH₄ or CoCl₂/LiAlH₄ in THF under H₂.⁴⁸ In both cases, the most active catalyst resulted from equimolar mixtures of metal chloride and LiAlH₄. Alkenes were classified into three groups according to decreasing ease of reduction by the iron (hydride or aluminide) system: (1) styrene, α-methylstyrene, safrole, isosafrole, indene, anethole, and isoprene were quickly reduced under most conditions; (2) cyclohexene and limonene were only partly reduced; (3) α-pinene, squalene, and furan were not reduced at all. Moreover catalytic activity was killed off when reductions of vinyl acetate, ethyl acrylate, allyl chloride, and acrylonitrile were attempted with the iron-based precipitate. The more active cobalt aluminide smoothly reduced cyclohexene, limonene, α-pinene, squalene, and even furan, albeit more slowly.

Ashby and Lin studied the reduction of alkenes and alkynes by LiAlH₄ in combination with first-row transition metal salts.⁴⁹ Equimolar mixtures of LiAlH₄ reacted with TiCl₃, VCl₃, CrCl₃, FeCl₂, FeCl₃, CoCl₂, or NiCl₂ in THF at low temperature and quantitatively reduced alkenes to alkanes (Table VIII). However when catalytic amounts of the metal halides were used, only CoCl₂, NiCl₂, and TiCl₃ gave alkanes in high yield. Few experimental details were reported. To determine the nature of reactive intermediates, product mixtures were quenched with D₂O and analyzed by gas chromatography-mass spectrometry. Reduction of 1-octene using stoichiometric amounts of FeCl₂ or catalytic

TABLE VIII. Reactions of Alkanes with LiAlH_4 -Transition-Metal Halides

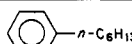
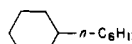
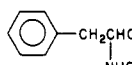
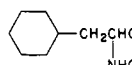
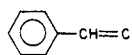
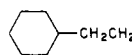
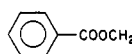
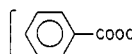
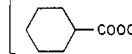
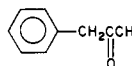
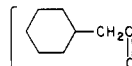
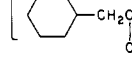
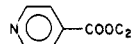
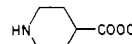
metal halide	alkene	reacn time, h	substrate recovery, %	alkane	yield, ^c %
FeCl_2^a	styrene	24	0	ethylbenzene	95
CoCl_2^b			5		92
NiCl_2^b			0		92
TiCl_3^b			0		94
FeCl_2^a	1-hexene	24	2	hexane	97
CoCl_2^b			0		97
NiCl_2^b			0		97
TiCl_3^b			0		96
FeCl_2^a	<i>cis</i> -2-hexene	24	0	hexane	98
CoCl_2^b			70		32
CoCl_2^a			0		98
NiCl_2^b			70		28
NiCl_2^a			3		95
TiCl_3			80		18
FeCl_2^a	<i>trans</i> -2-hexene	24	0	hexane	99
CoCl_2^a			0		96
NiCl_2^a			0		95
TiCl_3^a			10		90
FeCl_3^a	2-ethyl-1-hexene	24	20	3-methylheptane	80
		48	0		95
CoCl_2^b		48			35
CoCl_2^a		24	0		98
NiCl_2^b		48			15
NiCl_2^a		24	18		82
		48	0		95
TiCl_3^b		48			10
TiCl_3^a		24	10		88
		48	2		94
FeCl_2^a	cyclohexene	24	0	cyclohexane	96
CoCl_2^b		48	45		55
CoCl_2^a		24	0		96
NiCl_2^b		48	60		40
NiCl_2^a		24	2		94
TiCl_3^b		48	95		0
TiCl_3^a		24	60		45
		48	0		95

^aThe molar ratio of LiAlH_4 -metal halide-olefin is 1.0:10:2.0. ^bThe molar ratio of LiAlH_4 -metal halide-olefin is 1.0:0.1:2.0. ^cOf alkane.

amounts of CoCl_2 or NiCl_2 gave only 12–26% octane- d_1 , whereas 93% deuterium incorporation was observed using TiCl_3 . On the basis of these data, the reactive species was presumed to be a transition metal hydride, with homolytic dissociation of an intermediate transition metal-alkyl species and subsequent hydrogen abstraction from solvent accounting for the low deuterium content of the products. However, diphenylacetylene was reduced exclusively to *cis*-stilbene by LiAlH_4 - NiCl_2 , suggesting a more traditional heterogeneous hydrogenation mechanism for this process.

Ueno and Miya have shown that when excess sodium bis(2-methoxyethoxy)aluminum hydride (SMEAH, Vitride, Red-Al) reacted with CoCl_2 or $\text{Co}(\text{acac})_2$ in THF, a black precipitate was deposited with evolution of hydrogen.⁵⁰ The solid actively catalyzed reduction of styrene, ethyl acrylate, and cyclohexene under an atmosphere of hydrogen. No appreciable deactivation of the catalyst was observed during reduction, and samples more than 2 months old retained activity when stored under argon. Exposure to 1,3-cyclooctadiene (1,3-COD) did change the catalyst's properties: before exposure it failed to reduce cyclooctene, whereas after reduction of 1,3-COD, the catalyst smoothly hydrogenated cyclooctene to cyclooctane. While this behavior was not fully rationalized, cobalt hydride or a cobalt-bridged aluminum hydride were suggested as reactive intermediates.

TABLE IX. Reduction of Aromatic Compounds with NaBH_4 - RhCl_3 in EtOH

arom. compds.	temp, °C	products	yield, %
	40		quant
	30		94
	40		quant
	40		75
			25
	5		22
			21
	40		50

B. Reduction of Arenes

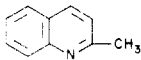
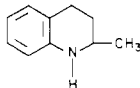



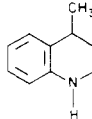


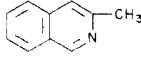
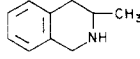

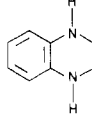
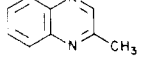
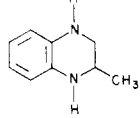
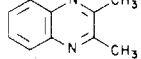
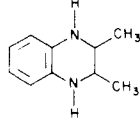
In examining the hydrogenolysis of aryl ketones by NaBH_4 -noble metal salts, Nishiki et al. observed that aromatic rings were readily saturated when treated with $\text{NaBH}_4/\text{RhCl}_3$ /ethanol in the absence of added hydrogen.⁵¹ Black precipitates were noted upon addition of NaBH_4 . Carboxylic acids, esters, and amides were unaffected by the reducing agent. In studies with β -phenethyl alcohol, the optimum yield of β -cyclohexylethyl alcohol (100%) required stoichiometric quantities of RhCl_3 . The stereochemistry of reduction of *p*-*tert*-butylphenol and *p*-*tert*-butyltoluene proved temperature-dependent over the range from -30°C to 60°C , with the *cis* isomers generally predominating. Best results were achieved with monosubstituted benzenes and pyridines (Table IX).

Grundt et al. discovered that benzene was reduced to cyclohexane using $\text{RhCl}_3/\text{NaBH}_4/\text{EtOH}$ at 30°C .⁵² Gas chromatographic analysis showed that both cyclohexene and cyclohexadiene were absent in the reaction mixture. This process also worked, but less well, with RuCl_3 or IrCl_3 . In all cases, the metal which had precipitated by the end of the reduction was inactive, suggesting, in accordance with earlier workers, that reduction was stoichiometric both in NaBH_4 and in metal.

The partial hydrogenation of several polycyclic aromatic hydrocarbons has also been achieved using $\text{RhCl}_3/\text{NaBH}_4$.⁵³

Reduction of heterocyclic compounds using CoCl_2 , NiCl_2 , CuCl_2 , or CrCl_3 in conjunction with NaBH_4 has been described by Nose and Kudo.⁵⁴ Best results were obtained with NiCl_2 and excess NaBH_4 in CH_3OH at room temperature. Conversion of several quinolines, isoquinolines, and quinoxalines to their tetrahydro derivatives are summarized in Table X. Contrary to the authors' mechanistic claims, several observations in the reduction of quinaldine (entry 1, Table X) suggested that Ni_2B and not NiCl_2 complexes were reduced by NaBH_4 : (1) the reduction was catalytic in NiCl_2 ; (2) in all reductions, exothermic formation of the characteristic boride was accompanied with vigorous H_2 evo-

TABLE X. Reduction of Heterocycles with $\text{NiCl}_2/\text{NaBH}_4$

compd	mmol	NaBH_4 , mmol	NiCl_2 , mmol	solvent	temp	product	yield, %
	8	32	1.4	MeOH	RT ^a		93.5
	8	32	4	MeOH	RT		82.8
	8	80	8	MeOH	RT		83.0
	8	96	8	MeOH	RT		86.7
	8	96	8	MeOH	RT		96.1
	8	160	16	MeOH	RT		54.2
	8	160	16	MeOH	RT		52.4
	8	64	8	MeOH	RT		99.2

^a RT = room temperature.

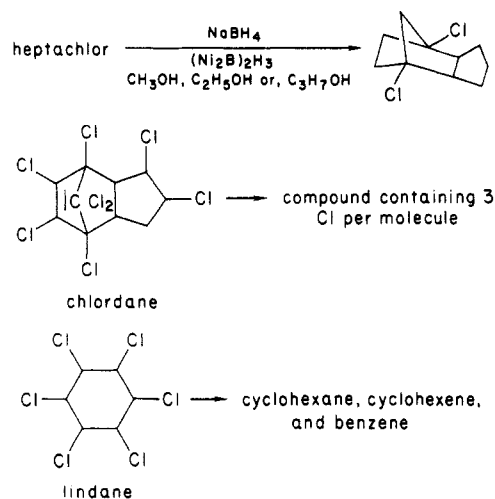
lution; (3) controls further indicated quinaldine was not reduced by catalytic hydrogenation over Ni_2B ; (4) tetrahydroquinaldine was produced (31% yield) by using preformed Ni_2B and excess NaBH_4 . The yield of desired product was somewhat lower, probably because working with the premade boride avoided the uncontrolled temperature rise during exothermic boride formation.

C. Reduction of Halides

1. Borides

Ordinarily sodium borohydride will not reduce unactivated organic halides. However Dennis and Cooper reported that the combination of Ni_2B catalyst with NaBH_4 in alcohol reductively dechlorinated toxic polychlorinated hydrocarbon pesticides (Table XI).⁵⁵ Besides the examples shown, both DDT and 2,4-D were extensively dechlorinated. Nickel boride prepared in anhydrous CH_3OH liberated more free chloride than did reductions in ethanol or 2-propanol. The presence of water-retarded reduction, and dehalogenation was less effective using CoCl_2 , MnSO_4 , or FeSO_4 . This method has also found application in the detoxification of polychlorinated biphenyls.^{56,57}

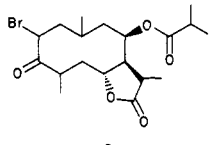
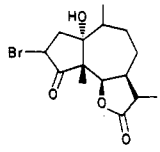
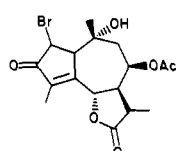
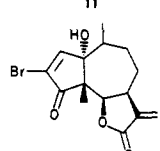
In contrast with an earlier report,³³ combining NiCl_2 with NaBH_4 (1.5 mol equiv) in DMF with no special precautions to exclude air generated a black precipitate of nickel boride which stoichiometrically reduced α -halo ketones to ketones (Table XII).⁵⁸ Reaction of *vic*-dibromides using the same procedure afforded alkenes in

TABLE XI. Reduction of Polychlorinated Organics with $\text{NiCl}_2/\text{NaBH}_4/\text{CH}_3\text{OH}$ 

80–90% yield. Alkyl chlorides were inert to this boride while bromides and iodides were reduced in only poor yield. In related work, Lin and Roth reacted $(\text{Ph}_3\text{P})_2\text{NiCl}_2$ with NaBH_4 in DMF or THF to reduce aryl bromides. Tris(triphenylphosphine)nickel(0) was suggested to be the active catalyst.⁵⁹

In a recent study of the $\text{PdCl}_2/\text{NaBH}_4/\text{CH}_3\text{OH}$ system, Satoh et al. found that aryl chlorides like β -chloronaphthalene and methyl *p*-chlorobenzoate were efficiently reduced to the corresponding arenes.⁶⁰ The same method selectively dechlorinated 5,7-dichloro-

TABLE XII. Reduction of α -Halo Ketones with Nickel Boride^{a-e}

entry	α -halo ketone reduced	% yield ^f
1	2-chlorocyclohexanone	75
2	2-bromocyclohexanone	90
3	2 α -bromocholestan-3-one	95
4	3 β -acetoxy-7 α -bromocholestan-6-one	95
5	<i>p</i> -bromophenacyl bromide	98
6	phenacyl bromide	98
7	α -bromocamphor	NR ^g
8	2 α -chlorocholest-4-en-3-one	70
9		85
10		90
11		95
12		50

^a All compounds were characterized by direct comparison (TLC, IR, NMR, and MS) with the authentic samples. ^b Yields refer to the isolated products of >90% purity. ^c Nickel chloride refers to the hexahydrate. ^d The rest of the material in case of entry 8 and 12 was the unreacted starting α -haloketone. ^e Substrates at entry 9, 10, 11, and 12 were prepared from the natural products available in our laboratory. ^f Of parent ketone. ^g NR = no reaction.

6,8-difluoro-1,4-dimethylnaphthalene to 5,7-difluoro-1,4-dimethylnaphthalene in 82% yield.⁶¹

2. Aluminides

Combinations of LiAlH₄ with Co(II), Ni(II), Fe(II), Fe(III), Mn(II), Ti(III), Cr(III), and V(III) halides in THF have been studied extensively by Ashby et al. as reducing agents for alkyl halides or tosylates, and aryl halides.⁶² Of these, only the CoCl₂-, NiCl₂-, and TiCl₃-based systems were active with catalytic quantities of the transition metal salt (Table XIII).

Using the reduction of bromocyclohexane with CoCl₂/LiAlH₄ as a representative case, Osby et al. demonstrated that the black precipitate of cobalt aluminide was primarily responsible for cyclohexane formation.¹⁴ The lithium borohydride reduction of halides like 1-chlorodecane was also promoted by CoAl in THF at 65 °C. Studies using LiAlD₄ with *cis*- and *trans*-4-bromo-*tert*-butylcyclohexane showed reduction occurred with complete stereochemical scrambling. Apparently THF and not the aluminum hydride served as the hydrogen donor in this radical process. In fact, stoichiometric amounts of CoAl were sufficient to reduce *cis*-4-bromo-4-deuterio-*t*-butylcyclohexane to a 43:57

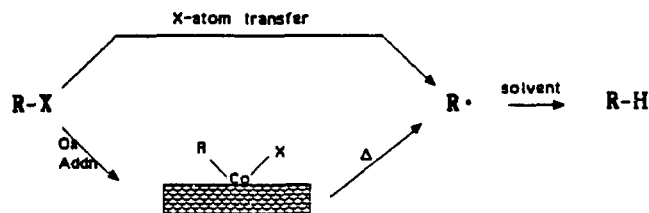


Figure 1. Mechanism of alkyl halide reduction.

mixture of *cis*- and *trans*-4-deuterio-*tert*-butylcyclohexane. Two plausible mechanisms were proposed (Figure 1): (1) halogen atom transfer from the alkyl halide to a metal radical on the aluminide surface, or (2) oxidative addition of the cobalt catalyst into the carbon-halogen bond. The latter process, besides involving a homolytic alkylcobalt cleavage well-known in the chemistry of vitamin B₁₂ and its analogues, was favored by several additional lines of evidence.⁶³ Both mechanisms correctly rationalize the secondary role of LiAlH₄ in regenerating active (reduced) aluminide catalyst.

A Japanese group recently reported that alkyl and aryl halides (including fluorides) were smoothly reduced using CeCl₃/LiAlH₄ in dimethoxyethane (DME) or THF at reflux (Table XIV).⁶⁴ Experiments with LiAlD₄ furnished products with no detectable deuterium incorporation (Table XIV, entries 4 and 10), again suggesting a radical pathway with H atom abstraction from DME or THF.

D. Reduction of Nitriles

In 1969 Satoh and Suzuki reported that nitriles (along with nitroarenes and amides) were reduced to primary amines by transition metal salt-NaBH₄ systems.⁶⁵ They found that CoCl₂ (2 equiv)/NaBH₄ (10 equiv) in CH₃OH was a particularly effective combination, which has since been applied to a wide variety of cases (Table XV).⁶⁶⁻⁷⁶ Because nitro group reduction required elevated temperatures, the selective reduction of *p*-nitrophenylacetone nitrile to *p*-nitrophenethylamine was readily achieved. In a preliminary communication about the mechanism of this reaction,¹² Heinzman and Ganem concluded that the cobalt boride formed in situ served as a true catalyst, strongly coordinating nitriles and activating them towards reduction by NaBH₄. Possible homogeneous and heterogeneous hydrogenations were unambiguously ruled out. Subsequent kinetic studies using benzonitrile indicated that at high nitrile:catalyst ratios, the rate of nitrile reduction was independent of its concentration. Moreover the rate of reduction exhibited a first-order dependence on NaBH₄ concentration over a 4-fold concentration range and several half-lives of benzonitrile. When the nitrile was reduced with equimolar mixtures of NaBH₄ and NaBD₄, a primary isotope effect ($k_H/k_D = 3.3$) was observed, consistent with rate-determining hydride attack on the coordinated nitrile by dissolved, uncoordinated borohydride.^{14,63} An optimized reduction procedure was developed using catalytic quantities of Co₂B in 2:1 THF:H₂O and avoiding the harshly acidic workup of Satoh and Suzuki.⁶⁵

Besides NaBH₄, certain amine boranes like *tert*-butylamine-borane (TAB) were found to reduce nitriles in CH₃OH in the presence of Co₂B (Table XVI). Although stoichiometric quantities of the boride were

TABLE XIII. Reduction of Halides by LiAlH₄-Transition-Metal Chlorides at Room Temperatures in THF Solvent^a

expt	halide substrate ^d	transition metal chloride ^b	reacn time, h	product	yield, %
1	1-chlorodecane ^e	None	24	<i>n</i> -decane	68
2		VCl ₃			75
3		CrCl ₃			90
4		MnCl ₂			19
5		FeCl ₃			100
6		FeCl ₂			95
7		FeCl ₂ ^c			85
8		CoCl ₂ ^c			100
9		NiCl ₂ ^c			100
10		TiCl ₃ ^c			100
11	1-bromodecane ^e	None	1	<i>n</i> -decane	92
12		VCl ₃			40
13		CrCl ₃			65
14		MnCl ₂			43
15		FeCl ₃			50
16		FeCl ₂			100
17		FeCl ₂ ^c			90
18		CoCl ₂			98
19		CoCl ₂ ^c			98
20		NiCl ₂			100
21		NiCl ₂ ^c			100
22		TiCl ₃			96
23		TiCl ₃ ^c			98
24	1-iododecane	None		<i>n</i> -decane	98
25		FeCl ₂			98
26		CoCl ₂ ^c			98
27		NiCl ₂ ^c			98
28		TiCl ₃ ^c			100
29	1-fluorodecane	None	24	<i>n</i> -decane	0
30		FeCl ₂			16
31		CoCl ₂ ^c			10
32		NiCl ₂ ^c			7
33		TiCl ₃ ^c			9
34	<i>n</i> -octyltosylate	None	24	<i>n</i> -octane	92
35		FeCl ₂			25
36		CoCl ₂ ^c			100
37		NiCl ₂ ^c			98
38		TiCl ₃ ^c			54
39	3-bromooctane	None	24	<i>n</i> -octane	75
40		FeCl ₂			90
41		CoCl ₂			98
42		NiCl ₂			92
43		TiCl ₃			88
44	bromocyclohexane	None	24	cyclohexane	0
45		FeCl ₂			97
46		CoCl ₂			99
47		NiCl ₂			99
48		TiCl ₃			100
49	chlorocyclohexane	None	24	cyclohexane	0
50		FeCl ₂			98
51		CoCl ₂			92
52		CoCl ₂ ^c			3
53		NiCl ₂			95
54		NiCl ₂ ^c			5
55		TiCl ₃			95
56		TiCl ₃ ^c			95
57	1-bromoadamantane	None	24	adamantane	70
58		FeCl ₂			100
59		CoCl ₂			100
60		NiCl ₂			100
61		TiCl ₃ ^c			100
62	chlorobenzene	None	24	benzene	0
63		FeCl ₂			72
64		CoCl ₂			25
65		CoCl ₂ ^c			0
66		NiCl ₂			100
67		NiCl ₂ ^c			0
68		TiCl ₃ ^c			45
69	bromobenzene	None	24	benzene	0
70		FeCl ₂			80
71		CoCl ₂			74
72		CoCl ₂ ^c			23
73		NiCl ₂			100
74		NiCl ₂ ^c			87
75		TiCl ₃ ^c			91
76	iodobenzene	None	24	benzene	38
77		FeCl ₂			98
78		CoCl ₂			98

TABLE XIII (Continued)

expt	halide substrate ^d	transition metal chloride ^b	reacn time, h	product	yield, %
79		NiCl ₂			100
80		TiCl ₃ ^c			92

^aAll reactions were carried out in THF at -78 °C for 10 min and then warmed to room temperature by removing the cooling bath. The reaction time was counted beginning with the period at -78 °C. Yields were determined by GLC using a suitable internal standard. ^bMolar ratio of LiAlH₄ to transition metal chloride is 1:1, except when noted. ^cUsed 10% molar equivalent. ^dHalide substrate was used in equivalent molar amount to LiAlH₄ except when noted. ^eHalide substrate was 1/2 equiv with respect to LiAlH₄.

TABLE XIV. Reduction of Organic Halides with LiAlH₄-CeCl₃

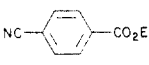
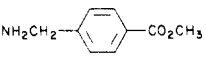
entry	substrate	conditions ^a	product	yield, % ^{b,c}
1	CH ₃ (CH ₂) ₁₁ F	THF, reflux, 3 h	C ₁₂ H ₂₆	90 (>99)
2	1-fluoronaphthalene	DME, reflux, 3 h	naphthalene	94 (>99)
3 ^d	1-fluoronaphthalene	DME, reflux, 3 h	naphthalene	0
4	1-fluoronaphthalene	DME, reflux, 3 h ^e	naphthalene ^f	92
5	2-fluorobiphenyl	DME, reflux, 5 h ^e	biphenyl	94 (98)
6	1-chloronaphthalene	THF, reflux, 3 h	naphthalene	95 (>99)
7 ^d	1-chloronaphthalene	THF, reflux, 3 h	naphthalene	37
8	4,4'-dichlorobiphenyl	DMF, reflux, 3 h	biphenyl	92 (>99)
9	2,4-dichlorophenol	THF, reflux, 20 h	4-chlorophenol	81

^aA molar ratio of 1:4.5:1.5 substrate/LiAlH₄/CeCl₃ was used unless otherwise stated. ^bIsolated yield. ^cThe figures in parentheses indicate the yields determined by GLC. ^dThe reaction was carried out in the absence of CeCl₃ under the same conditions. ^eLiAlD₄ was used in place of LiAlH₄. ^fThe product was identified by ¹H NMR and mass spectra. ^gUnder irradiation with a 200-W W-lamp.

TABLE XV. Reduction of Nitriles Using CoCl₂-NaBH₄

nitrile	product (yield)	ref
C ₆ H ₅ CN	C ₆ H ₅ CH ₂ NH ₂ (72%)	65
C ₆ H ₅ CN	C ₆ H ₅ CH ₂ NH ₂ (91%)	14
<i>p</i> -NO ₂ -C ₆ H ₄ CN	<i>p</i> -NO ₂ -C ₆ H ₄ CH ₂ NH ₂ (60%)	65
<i>p</i> -OH-C ₆ H ₄ CN	<i>p</i> -OH-C ₆ H ₄ CH ₂ NH ₂ (70%)	65
β-cyanopyridine	β-aminomethylpyridine (35%)	65
furonitrile	furfurylamine (75%)	65
C ₆ H ₅ CH ₂ CN	C ₆ H ₅ CH ₂ CH ₂ NH ₂ (74%)	12
CH ₂ =CHCN	CH ₂ =CHCH ₂ NH ₂ (70%)	65
		12
	CH ₃ CH(CH ₂ OH)CH ₂ CH ₂ NH ₂ (80%)	66
NC(CH ₂) ₂ NH(CH ₂) ₃ NH(CH ₂) ₄ NH ₂	H ₂ N(CH ₂) ₃ NH(CH ₂) ₃ NH(CH ₂) ₄ NH ₂ (70%)	67
<i>n</i> -C ₇ H ₁₅ CN	<i>n</i> -C ₇ H ₁₅ CH ₂ NH ₂ (80%)	65
C ₆ H ₅ CH(OH)CN	C ₆ H ₅ CH(OH)CH ₂ NH ₂ (80%)	65, 68
<i>n</i> -C ₆ H ₁₃ CH(OH)CN	<i>n</i> -C ₆ H ₁₃ CH(OH)CH ₂ NH ₂ (77%)	68
		69
		70
		72
		73
		74
		75
		76

TABLE XVI. Reduction of Organic Compounds Using Co₂B-TAB

substrate	conditions ^a	product (yield, %)
PhCN	2 equiv TAB, 3 h	PhCH ₂ NH ₂ (75%)
PhCH ₂ CN	2 equiv TAB, 7 h	PhCH ₂ CH ₂ NH ₂ (88)
CH ₃ (CH ₂) ₄ CN	2 equiv TAB, 2.5 h	CH ₃ (CH ₂) ₅ NH ₂ (81)
	4 equiv TAB, 12.5 h	 (75)
PhCONH ₂	2 equiv TAB, 3 h	NR ^b
PhCH=CHCO ₂ CH ₃	2 equiv TAB, 3 h	PhCH=CHCO ₂ CH ₃ (75)
CH ₃ (CH ₂) ₅ C≡CH	2 equiv TAB, 2 h	octene (25) ^c octane octyne (75)

^a All reactions were run with 1 equiv of Co₂B at reflux in CH₃OH under N₂. ^b No reaction. ^c Yield determined by GC.

necessary,¹² "spent" boride from TAB nitrile reductions still actively catalyzed reduction of nitriles by NaBH₄. This unusual behavior was later attributed to pH differences between the two reactions.¹⁴ When the pH of TAB-CH₃OH solutions was brought to ca. 8-9 (as in NaBH₄-CH₃OH mixtures), the reduction of benzonitrile to benzylamine became catalytic in Co₂B. Since TAB did not decompose to liberate H₂, little or no reduction of alkenes or alkynes occurred, making it a much more selective method (Table XVI).

E. Reduction of Nitro Compounds

1. Nitroarenes

The reduction of aromatic nitro compounds to amines is an important synthetic reaction, especially in large-scale pharmaceutical and industrial chemical processes. Suspensions of tin and iron in acid are commonly employed, as is catalytic hydrogenation. A special example of the latter method is the use of NaBH₄ with Pd/C catalyst in protic solvents in converting nitrobenzene to aniline.⁷⁷

The combination of NaBH₄ with transition metal salts to reduce nitroarenes has been investigated in detail. In 1962 Brown and Sivasankaran reported that platinum metal salts (e.g. Ru, Rh, Pd, Os, Ir, Pt), when treated with aqueous or ethanolic NaBH₄, formed finely divided black precipitates which catalytically reduced nitrobenzene to aniline as NaBH₄ decomposed to H₂.^{22b,78} In 1969, Satoh and Suzuki described several examples of the same reaction using CoCl₂/NaBH₄ in either CH₃OH or dioxane (Table XVII) at 40-100 °C.⁶⁵ Yields were modest, and both gas evolution and the formation of black precipitates were noted. In 1970, upon reinvestigating this process, the same research group found that products varied with the reaction conditions and with the choice of metal salt. Nitroarenes furnished azoxy compounds by using CoCl₂ (Table XVIII) and amines by using CuCl₂.⁷⁹ Experimental details rationalized the apparent contradiction

in the cobalt experiments: the later paper⁷⁹ described the addition of NaBH₄ at 20 °C to a stoichiometric mixture of nitrobenzene and CoCl₂ in CH₃OH slowly enough to prevent formation of a black precipitate. In the absence of boride, NaBH₄ reduction of an unspecified homogeneous cobalt complex must have occurred. Recently Osby noted the same anomalous behavior in the complexation of *nitroalkanes* with Co(II) salts (*vide infra*).⁶³

Nickel chloride exhibited no such peculiarities, and has been used with NaBH₄ to reduce nitroarenes to anilines in good yield (Table XIX).⁸⁰ Nickel boride supported on charcoal converted *p*-nitrophenylglycosides to *p*-aminophenylglycosides.⁸¹ Other nitroarene reductions using CuCl/NaBH₄/EtOH and FeCl₃/NaBH₄/EtOH have been reported which also probably involve boride catalysts.^{82,83}

Numerous homogeneous systems comprised of NaBH₄ in combination with soluble transition metal complexes have also been developed for nitro group reductions, but are reviewed elsewhere.⁵

2. Nitroalkanes

Nitroaliphatic compounds have traditionally been reduced to amines by high-pressure hydrogenation, LiAlH₄ or aluminum amalgam. More recently, the use of transfer hydrogenation⁸⁴ and of low-valent titanium reagents⁸⁵ has been recommended. In 1985 Osby and Ganem reported that NiCl₂/NaBH₄/CH₃OH rapidly reduced a variety of primary, secondary, and tertiary nitroalkanes to amines at room temperature (Table XX).¹³ Nickel boride, prepared in situ, was the active catalyst, requiring dissolved NaBH₄ (and not H₂) as the reducing agent. The reagent selectively reduced nitrocyclohexane in the presence of hexanenitrile. While methanolic CoCl₂/NaBH₄ completely failed to reduce nitroalkanes (no boride was formed), premade Co₂B with NaBH₄ did slowly convert nitrocyclohexane to cyclohexylamine; however, no selectivity between nitriles and nitro compounds could be achieved.⁶³

F. Reduction of Other Nitrogenous Functional Groups

1. Amides

Besides nitriles and nitro compounds, Satoh and Suzuki reported that primary amides were also reduced to amines using CoCl₂/NaBH₄/CH₃OH.⁶⁵ However Heinzman and Ganem were unable to reproduce the reduction of benzamide to benzylamine (60% yield reported)⁶⁵ even in the presence of excess boride.¹² Other workers have apparently had similar difficulties.⁸⁶

2. Oximes

In 1984, Ipaktschi observed that saturated and unsaturated oximes were exhaustively reduced to satu-

TABLE XVII. Reduction of Aromatic Nitro Compounds with NaBH₄-CoCl₂ System

nitro compd	product	solvent (temp)	yield, %
<i>p</i> -NO ₂ C ₆ H ₄ CH ₂ CN	<i>p</i> -NH ₂ C ₆ H ₄ (CH ₂) ₂ NH ₂	CH ₃ OH (40°)	50
<i>o</i> -NO ₂ C ₆ H ₄ COOH	<i>o</i> -NH ₂ C ₆ H ₄ COOH	dioxane (bp) ^a	40
<i>p</i> -NO ₂ C ₆ H ₄ OH	<i>p</i> -NH ₂ C ₆ H ₄ OH	dioxane (bp)	35
<i>p</i> -HOC ₆ H ₄ CH ₂ CH(NO ₂)CH ₃	<i>p</i> -HOC ₆ H ₄ CH ₂ CH(NH ₂)CH ₃	C ₂ H ₅ OH (bp)	45
<i>p</i> -NO ₂ C ₆ H ₄ SO ₃ H	<i>p</i> -NH ₂ C ₆ H ₄ SO ₃ H	C ₂ H ₅ OH (bp)	38

^a Boiling point.

TABLE XVIII. Reduction of Monosubstituted Nitrobenzenes to Azoxybenzenes with Samarium Borohydride-Cobaltous Chloride

	yield, ^a %	Hammett's constant σ
<i>p</i> -CO ₂ Me	87	+0.636
<i>p</i> -CO ₂ Et	86	+0.522
<i>p</i> -CN	86	+0.628
<i>p</i> -Cl	79	+0.227
<i>p</i> -CO ₂ H	71	+0.132
H	62	+0
<i>p</i> -Me	40	-0.170
<i>p</i> -OMe	19	-0.263
<i>m</i> -Cl	84	+0.378
<i>m</i> -CO ₂ Me	84	+0.315

^a Of azoxy compound.

TABLE XIX. Reduction of Aromatic Nitro Compounds with NaBH₄-NiCl₂

nitro compd ^a	NiCl ₂ , 6H ₂ O, mmol	NaBH ₄ , ^b mmol	product (prim amine)	
			R	yield, %
H	16	64	H	76.3
<i>p</i> -CH ₃	16	32	<i>p</i> -CH ₃	95.0
<i>m</i> -CH ₃	16	32	<i>m</i> -CH ₃	94.6
<i>o</i> -CH ₃	16	32	<i>o</i> -CH ₃	80.5
<i>p</i> -CH ₃ O	16	32	<i>p</i> -CH ₃ O	88.9
<i>p</i> -Cl	16	32	<i>p</i> -Cl	89.1
<i>p</i> -OH	16	32	<i>p</i> -OH	88.2
<i>p</i> -COOH	16	32	<i>p</i> -COOH	77.6
<i>o</i> -COOH	8	32	<i>o</i> -COOH	85.6
1-nitronaphthalene ^c	16	32	1-naphthylamine ^c	85.5

^aThe amount of nitro compound was 8 mmol. ^bThe reaction time was 30 min, and the reaction temperature was 20 °C. ^cThe chemical name.

TABLE XX. NaBH₄-Ni₂B Reductions of Nitro Aliphatic Compounds

reactant ^a	product ^b	yield ^c
		68% ^d
	2	66% ^d
C₈H₁₇NO₂ 6	C₈H₁₇NH₂ 7	61%
		76%
		64%
		50% ^e
		69%

^aAll reductions were carried out according to the representative procedure in section IIE2. ^bProducts were identified by comparison with authentic samples, where possible. Satisfactory IR, NMR, and mass spectra were obtained for all new compounds. ^cYields reported are for isolated, pure compounds. ^dIsolated as its HCl salt; lower yields are due to appreciable water solubility of this product. ^eProduct stirred for 2 days at room temperature before workup.

rated amines at -30 °C using NiCl₂/NaBH₄/CH₃OH (Table XXI). Unsaturated oximes furnished allylic amines when the reduction was carried out with

TABLE XXI. Reduction of Oximes with NiCl₂/NaBH₄

substrate	product	yield, %
		94
		92
		92
		70
		95
		90
		95
		95

MoO₃/NaBH₄. Moreover the stereochemistry of reduction was decidedly different with the two reagent systems. While the reduction mechanisms were not established, the NiCl₂ method was shown not to involve heterogeneous hydrogenation.⁸⁷

3. Azoxy, Azo, Nitroso Compounds, and Hydroxylamines

In their 1969 survey of heterogeneous boride catalysts, Pratt and Swinden found that Co₂B catalyzed the decomposition of H₂O₂ and promoted the reduction of nitrate to ammonia in the presence of NaBH₄. While hydrazine hydrate was catalytically decomposed to ammonia (inter alia) by the boride, the same mixture quantitatively reduced azobenzene to hydrazobenzene in ethanol, apparently by transfer hydrogenation.⁸⁸ The combination of CoCl₂ with NaBH₄ in CH₃OH (-60 °C) was later shown to reduce azoxybenzenes, azobenzenes, and nitrosobenzenes to hydrazobenzenes. Prolonged reduction of the hydrazo compounds at room temperature led to the corresponding anilines. However aliphatic azo compounds like 2,3-diazanorbornene and *trans*-di-1-adamantylidiazene did not react.⁸⁹ More recently the same reduction of nitroso-, azoxy-, azo-, and hydroxylaminobenzene to aniline was achieved with NiCl₂/NaBH₄/CH₃OH.⁹⁰

4. Isoxazolidines

In studying the use of nitrene cycloadditions for the synthesis of anatoxin-A, Tufariello et al. found that anhydrous NiCl₂/LiAlH₄ reductively cleaved isoxazolidines to aminoalcohols (Table XXII). Substituting anhydrous CoCl₂ for NiCl₂ considerably attenuated the yield of isolated product.⁹⁰

TABLE XXII. The Reduction of Isoxazolidines with NiCl₂-LiAlH₄

substituents ^a	product, % yield
R ₁ , R ₂ = Ph, R ₃ = H, R ₄ = <i>n</i> -Bu	92
R ₁ , R ₂ = (CH ₂) ₄ , R ₃ = H, R ₄ = Ph	87
R ₁ , R ₂ = (CH ₂) ₄ , R ₃ = H, R ₄ = PhCH ₂ I salt	76
R ₁ , R ₂ = (CH ₂) ₄ , R ₃ = H, R ₄ = <i>n</i> -Bu	97
R ₁ , R ₂ = (CH ₂) ₄ , R ₃ , R ₄ = Ph	95

^aThe isoxazolidines were prepared by nitron-alkene cycloaddition reactions.

G. Deoxygenation Reactions

1. Sulfoxides

A recent review on sulfoxide reduction comprehensively tabulated methods involving low-valent metals such as CrCl₂, TiCl₂, TiCl₄, Mo(CO)₆, Fe(CO)₅, and others.⁹¹ In 1971 Chasar noted that dialkyl, arylalkyl, and diaryl sulfoxides were quantitatively reduced to sulfides within 1 h using CoCl₂ (2 equiv) with NaBH₄ (10 equiv) in ethanol at room temperature (Table XXIII). However with dibenzylsulfoxide and tetramethylenesulfoxide, cleavage reactions producing volatile byproducts were suggested to account for the low mass recovery and poor yield of sulfide.⁹² Chung and Han recently rediscovered this method and reported several additional examples.⁹³ Some hydrogenolysis of dibenzyl sulfoxide to benzyl mercaptan was detected. Cobalt boride, noted by both groups, was apparently catalytic (entry 3, Table XXIII). Sulfones were not affected.

The mechanism of sulfoxide reduction has been investigated by Osby.⁶³ Neither Co₂B alone (premade in EtOH, washed) nor boride under an atmosphere of H₂ was capable of reducing di-*n*-butyl sulfoxide in the normal reaction period (2 h), although di-*n*-butyl sulfide was produced in 35% yield after 2 days. In sharp contrast, mixtures of Co₂B and NaBH₄ furnished the sulfide in 50–60% yield. As mentioned earlier, working with premade boride avoided the initial temperature rise and resulted in moderately slower reaction rate. Thus Osby's work demonstrated that two reduction mechanisms were possible, but that the NaBH₄-based

process was faster than heterogeneous hydrogenation.

In dimethyl sulfoxide solvent, the combination of NaBH₄ with CoCl₂ or CeCl₃ selectively reduced aldehydes in the presence of ketones. Also α,β-unsaturated ketones were converted predominantly to allylic alcohols. Not surprisingly, copious quantities of dimethyl sulfide were also produced.⁹⁴

2. Phosphine Oxides

Phosphine oxides were rapidly deoxygenated to the corresponding phosphines using LiAlH₄/CeCl₃/THF.⁶⁴

3. Ethers and Esters

While P-2 nickel boride does not hydrogenolyze allylic, propargylic, and benzylic substituents, recent developments in boride chemistry have made this transformation possible. In 1984, Ipaktschi found that NiCl₂/NaBH₄/CH₃OH constituted an effective system for reductive removal of allylic, propargylic, and benzylic acetate esters (Table XXIV).⁹⁵ Equimolar amounts of the unsaturated ester and NiCl₂, when treated with excess NaBH₄ (10 equiv) for 30 min at 0 °C, afforded (mixtures of) alkenes and alkanes. Likewise cinnamyl alcohol furnished a 1:1 mixture of 1-phenylpropane and 1-phenylpropene. Interestingly, *p*-anisyl acetate was reduced in CH₃OD to a 35:65 mixture of mono and undeuterated 4-methylanisole. More highly deuterated species were not detected.

Using nickel boride prepared in anhydrous diglyme from NiCl₂ and NaBH₄, Sarma and Sharma showed that the ease of reductive removal of allylic substituents followed the order: allylic OCH₃ < OH < OSiMe₃ < OCOCH₃ < OCOCF₃. In comparing nickel boride with Raney nickel, the former was judged superior for reductive removal of an allylic acetate whereas the latter more efficiently deoxygenated allylic benzyl ethers. Consistent with earlier findings, reductions of 3β-acetoxycholest-4-ene run in CH₃CH₂OD resulted in only 20% deuterium incorporation.⁹⁶ The same workers reported the reductive cleavage of allylic alcohols to alkenes in a one-pot process via the corresponding trimethylsilyl ethers (Table XXV).⁹⁷

4. Aryl Ketones

Aromatic ketones like benzophenone, fluorenone, and acetophenone and their corresponding benzylic alcohols can be reductively deoxygenated with PdCl₂/NaBH₄/

TABLE XXIII. Reduction of Sulfoxides by CoCl₂/NaBH₄/EtOH

entry	substrate	product (% yield)	mol ratios of sub/Co(II)/NaBH ₄	reacn time, h
1	<i>p</i> -tolyl sulfoxide	starting material	1/0/2.7	48
2	<i>p</i> -tolyl sulfoxide	<i>p</i> -tolyl sulfide (95)	1/1/2.7	4
3	<i>p</i> -tolyl sulfoxide	<i>p</i> -tolyl sulfide (60)	1/0.1/2.7	48
4	phenyl sulfoxide	phenyl sulfide (90)	1/1/2.7	4
5	<i>p</i> -chlorophenyl sulfoxide	<i>p</i> -chlorophenyl sulfide (96)	1/1/2.7	4
6	<i>n</i> -butyl sulfoxide	<i>n</i> -butyl sulfide (80)	1/1/2.7	4
	<i>n</i> -butyl sulfoxide	<i>n</i> -butyl sulfide (98)	1/2/10	2
7	benzyl sulfoxide	benzyl sulfide (72)	1/1/2.7	5
8	phenyl vinyl sulfoxide	phenyl ethyl sulfide (60)	1/2/5	4
9	phenyl vinyl sulfoxide	phenyl ethyl sulfide (56)	1/1/2.7	4
		phenyl ethyl sulfoxide (44)		
10	phenyl methyl sulfoxide	phenyl methyl sulfide (98)	1/2/10	2
11	dibenzyl sulfoxide	dibenzyl sulfide (10)	1/2/10	2
12	thioxanthine sulfoxide	thioxanthone (100)	1/2/10	2
13	(CH ₂) ₄ SO	–	1/2/10	2
14	diphenyl sulfone	diphenyl sulfone (100)		

TABLE XXIV. Reduction of Allylic and Propargylic Acetates Using $\text{NiCl}_2/\text{NaBH}_4$

reactant	product	% yield
		93
		>95
		87
		>95
		90

CH_3OH at room temperature.⁶⁰ Hindered steroidal ketones were also reduced to alcohols in good yield. A black precipitate noted during reduction was termed elemental palladium, but may well have been palladium boride.⁷⁸

H. Desulfurization Reactions

The first use of Ni_2B to desulfurize organic structures was reported in 1963 when Truce and Perry reduced thioketals and thioacetals with excess $\text{NiCl}_2/\text{NaBH}_4$ in EtOH under N_2 at reflux.⁹⁸ That method was later extended to the desulfurization of mercaptans, sulfides, and sulfoxides in good yield.⁹⁹ Besides ease of preparation, Ni_2B offered several advantages over Raney nickel, among them: (1) the boride could selectively remove a single sulfur from a thioketal, and (2) desulfurization could be accomplished in the presence of sulfones.

A later study described the desulfurization of heterocyclic thiols with Ni_2B at reflux in ethylene glycol or in aqueous solution at 200 °C.¹⁰⁰ Yields were not as high as those obtained using Raney nickel. Paz et al. also used $\text{NiCl}_2/\text{NaBH}_4$ to desulfurize peptides for mass spectrometric sequence analysis.¹⁰¹









In 1973 Boar et al. desulfurized ethylene dithioacetals and hemithioacetals with Ni_2B and noted that the rate of reduction decreased as borohydride decomposition raised the pH of the medium. Optimum reaction conditions were developed, consisting of ethylene glycol or ethanol-boric acid as solvent, and the method was then applied to a new synthesis of triterpene-2-enes.¹⁰²

The reductive fission of sulfides and thioketals with CuCl_2 (2 equiv) and LiAlH_4 (4 mole equiv) has been investigated by Mukaiyama et al.¹⁰³ Benzophenone ethylene dithioketal, diphenylmethyl phenyl sulfide, and several 2-pyridyl sulfides were reductively desulfurized at reflux in THF after 3 h. Yields were enhanced when ZnCl_2 was added to the medium. Narasaka et al. later reported the total synthesis of α -cis-bergamotene using this method.¹⁰⁴

TABLE XXV. Nickel Boride Reduction of Me_3Si Ethers of Allylic Alcohols

entry	substrate	product	time, h	yield, %
1	cholest-4-en-3 β -ol	cholest-4-ene	6	80
2	cholest-5-en-4 β -ol	cholest-5-ene	6	50
3			3	60
4			3	60
5			1	80
6			1.5	80
7			2	75
8			6	30

TABLE XXVI. Hydroboration of Alkenes with $\text{CoCl}_2/\text{NaBH}_4^a$

alkene	product ^b	yield, % ^c
$\text{CH}_3(\text{CH}_2)_7\text{CH}=\text{CH}_2$	$\text{CH}_3(\text{CH}_2)_7\text{CH}_2\text{CH}_2\text{OH}$	70
		68 ^d
		85
		90
		70

^aThe reactions were carried out using 40 mmol of alkenes, 20 mmol of NaBH_4 and 10 mmol of CoCl_2 in THF (40 mL) under nitrogen atmosphere. THF used was distilled over benzophenone-sodium. Cobalt(II) chloride supplied by Alfa-USA and the sample prepared by the dehydration of $\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$ using 2,2-dimethoxypropane work equally well. Sodium borohydride supplied by Fluka-Switzerland and the sample supplied by Loba-Cheme-India give identical results. ^bProducts obtained after oxidation with $\text{H}_2\text{O}_2/\text{NaOH}$. The products were identified by spectral data (IR, ^1H NMR and ^{13}C NMR) and comparison with the data reported in the literature. ^cYields are of the isolated and distilled products. ^dThe isomeric 1-phenylethanol is present to the extent of 18%. Products in other cases contain only small amount of the isomeric alcohols (<5%).

The combination of FeCl_2 with sodium triethylborohydride on alumina in benzene-THF at room temperature turned black and desulfurized thiols and thionketones in a heterogeneous reaction. The order of mixing proved very important in this process: much lower conversions resulted when the FeCl_2 was first deposited on alumina. Yields were also poorer with lithium triethylborohydride.¹⁰⁵

I. Miscellaneous Reactions

1. Formation of Amine Boranes

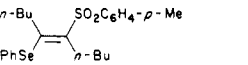
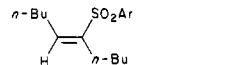
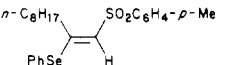
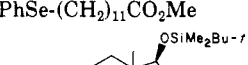
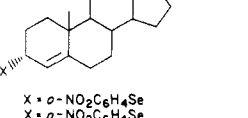
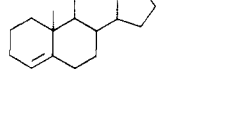
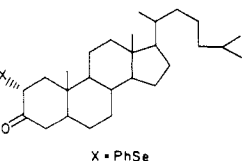
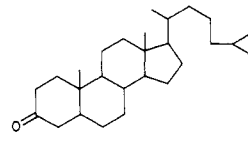

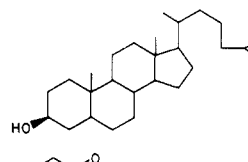
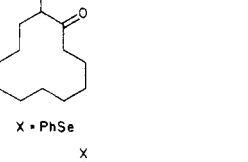
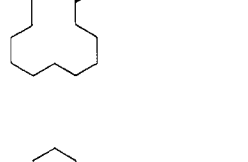
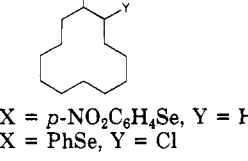
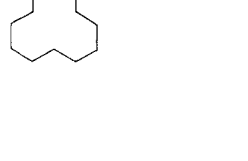
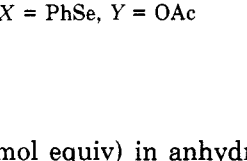
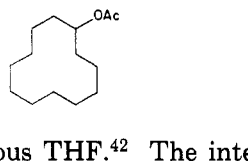
A new synthesis of amidine-based amine boranes was recently reported by Okamoto et al. These useful reducing agents, customarily prepared under aprotic conditions, were easily produced by treating the corresponding amines (2-aminopyridine, 2-aminopyrimidine) with excess NaBH_4 and $1/2$ mol equiv of CoCl_2 in aqueous solvent.¹⁰⁶ Use of FeSO_4 also gave amine boranes in good yield. However, 4-aminopyridine and 2-aminomethylpyridine did not form borane complexes, suggesting that metal-amidine chelation played an important mechanistic role.

Osby et al. showed that Co_2B was formed in this process and altered the normal mode of borohydride decomposition in water or alcohol. For instance, 2-aminopyridine alone had no effect on the rate of H_2 evolution from an aqueous solution of NaBH_4 , nor did was any amine borane formed. However mixing the amine with CoCl_2 or Co_2B caused considerable foaming and afforded the corresponding amine borane.¹⁴

2. Hydroboration

In 1984, Satyanarayana and Periasamy reported that alkenes like 1-decene could be hydroborated by using a combination of CoCl_2 (0.5 mol equiv) and NaBH_4 (1

TABLE XXVII. Reductive Deselenization with $\text{NiCl}_2/\text{NaBH}_4$

selenide	product	yield
		95%
	$n\text{-C}_{10}\text{H}_{21}\text{SO}_2\text{C}_6\text{H}_4\text{-}p\text{-Me}$	80%
	$\text{CH}_3(\text{CH}_2)_{10}\text{CO}_2\text{CH}_3$	90%
		83-91%
		60%
		34%
		93%
		71-100%
		50%

mol equiv) in anhydrous THF.⁴² The intermediate, presumed to be an organoborane, underwent protonolysis (with 3 N HCl) or oxidation (with H_2O_2) to afford *n*-decane (40-50%) or 1-decanol (70%), respectively (Table XXVI). Few experimental details were recorded.

This system was reinvestigated by Osby et al. who showed it to be a complex heterogeneous reaction in which a fine black precipitate of cobalt boride slowly formed alongside undissolved NaBH_4 and CoCl_2 .¹⁴ Nevertheless the supernatant retained its characteristic blue color, even after prolonged reaction. Controls showed that BH_3 , if generated in situ, would continue to react with CoCl_2 to form more boride. Efforts to trap BH_3 using 1,5-cyclooctadiene were inconclusive.

3. Epoxide Opening

The reduction of epoxides to alcohols has been achieved by using $\text{NiCl}_2/\text{LiAlH}_4$ in THF at room temperature. Whereas LiAlH_4 alone reduced styrene oxide to α -phenylethanol, the $\text{NiCl}_2/\text{LiAlH}_4$ system afforded β -phenylethanol exclusively (95% yield).⁹⁰ The same

primary alcohol was obtained with Raney nickel.

4. Deselenation

In 1984, Back published a convenient method for the reductive deselenization of alkyl, allyl, and alkenyl selenides with $\text{NiCl}_2/\text{NaBH}_4$ in $\text{THF}-\text{CH}_3\text{OH}$ at 0°C . Little or no alkene reduction was observed under these conditions, and selenides could be cleaved in the presence of the analogous sulfides, presumably because of the greater C-S bond strength. Sulfones, ketones, and acetates also resisted reduction (Table XXVII).¹⁰⁷

J. Conclusion

It is apparent from the literature reviewed here that transition metal borides and aluminides constitute an exciting variety of active heterogeneous catalysts. With a growing appreciation of the factors which govern catalyst activity and selectivity, the chemist may now rationally design specific borides or aluminides by proper choice of reagents and careful adjustment of reaction conditions. Many such materials have already found application in industrial chemical processes. Others await discovery as key catalysts for new and emerging synthetic chemical methods.

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