

# INDUSTRIAL APPLICATIONS OF BORON COMPOUNDS

RAYMOND THOMPSON

*Borax Consolidated Limited, Borax Research Centre, Cox Lane,  
Chessington, Surrey, UK*

## ABSTRACT

An inverse proportionality exists between industrial production and scientific interest in boron compounds. Despite the vast amount of research which has been done both academically and industrially, the four simple substances borax, boric acid, calcium borate and sodium perborate account for 99 per cent of the industrial applications in tonnage (production being over two million tons annually) and monetary terms. Several other metal borates, fluoborates and refractory compounds (including alloys) are used at the thousands of tons level, but the academically fascinating boron hydrides, carboranes and related materials, research on which accounts for 99 per cent of publications in boron chemistry during the past few decades, are used hardly at all.

There is an inverse proportionality between industrial importance and scientific interest in the case of boron compounds. Borax, or sodium tetraborate, holds practically no attention in the academic world, save possibly as an adjuvant in conducting experiments on other materials. It is a simple salt which dissociates in solution and whose properties have, with a few exceptions, been known for many years. Seldom does a paper devoted to it appear in the scientific literature. Yet its industrial production is well over a million tons a year, placing it in the commodity class, and its uses in technology are legion. On the other hand, innumerable papers are published annually, and have been for the past two or three decades, on the boranes and related compounds. But despite the vast amount of research undertaken in universities and other establishments throughout the world, the uses of these materials are quite negligible; annual 'production' is only on the scale of a minor laboratory reagent and can be measured in kilogrammes.

Between these two extremes lie first the simple inorganic compounds calcium borate, sodium perborate, boric acid and boric oxide. World production statistics are difficult to derive, but best estimates of annual tonnages put them at (in thousands of tons) as 750, 400, 120 and 30 respectively. The last three are made from the tonnages of the first and, of course, of borax itself. There is then a range of borates of other metals, several fluoborates and a number of alloys and refractory compounds which are in the one thousand to five thousand tons class. Finally there are several others, mostly inorganic, which are made commercially in smaller quantities but whose

importance and value are still significant. The free element is included in this last category. As if to maintain this inverse proportionality 'rule', scientific interest and attention increases through these categories as the level of production decreases. Sheer volume of production is not, of course, the only measure of relative importance. Producers of boron compounds are more concerned with sales value, and with profit levels. However, if one takes total sales volume instead of weight as an indication of usefulness, the result is very much the same and each of these three intermediate categories is left in the same relative position to all others.

Reference will be made in this paper to the major existing uses of compounds in all of these categories, together with an indication of development areas and the author's personal forecasts of future trends. But it is appropriate first of all to describe briefly the structure of the producer industry and the inter-relationship of the compounds discussed.

### OCCURRENCE, MINING AND REFINING

Borax itself is made nowadays by one of two methods: either from the native sodium tetraborates tincal (the decahydrate) and kernite (a fibrous tetrahydrate) which occur in solid form, or from lake brines where the borax is present along with other salts. By far the major source is the deposit at Boron in the Mojave Desert of California, which is worked by US Borax and Chemical Corporation, a subsidiary of RTZ Borax. A similar, though smaller, deposit is operated by the same group in Argentina. Both are by open pit methods, and the famous mine at Boron is shown in *Figure 1*. The principal borate-containing brine lake is also in California and is known as Searles Lake. The brine is processed by subsidiaries of Kerr McGee and of Stauffer. The other primary ore, colemanite,  $2\text{CaO}\cdot 3\text{B}_2\text{O}_3\cdot 5\text{H}_2\text{O}$ , comes



*Figure 1.* Open pit.

mainly from Turkey where production is now estimated at around seven hundred thousand tons annually. Mining is principally in the hands of local private and state-controlled companies. An important sodium borate deposit was discovered in Turkey a few years ago, but it is not yet worked on a large scale. More recently several companies have indicated plans to mine and upgrade colemanite in California (which is how and where the modern borate industry began a century ago) but the mineral is probably not present in the quantities which will lead to a major operation. The polarization of sodium mineral production in the western hemisphere, which began fifty years ago, and the calcium ore in Turkey is thus for the time being maintained. Several other minerals are mined in smaller, but in some cases growing, tonnages. They include the calcium-magnesium borate, hydroboracite; ulexite, a sodium-calcium ore; and, in the USSR, the borosilicate ores datolite and danburite. The hot spring soffioni, or fumaroles, of Tuscany which contain boric acid are no longer of commercial significance.

### THE MAJOR BULK PRODUCTS

Although it perhaps slightly begs the question of the title of this paper, one of the most important applications of both sodium and calcium borates is in the production of boric acid. This is done invariably by double decomposition of the ore with sulphuric acid, separating the byproduct metal sulphate by fractional crystallization or filtration as appropriate (*Figure 2*). The other major derived product is sodium perborate,  $\text{NaBO}_3 \cdot 4\text{H}_2\text{O}$ . This can be made either from borax or from colemanite, most usually the former. Here again the chemistry is basically simple, but as with borax and boric acid production attention to processing detail is important to attain the desired purity, particle size and, in the specific case of the perborate, stability. Sodium hydroxide is added to borax in order to increase the soda to boric oxide ratio to the metaborate,  $\text{NaBO}_2$ , which in turn is treated with hydrogen peroxide. When colemanite is used for this purpose it is first treated with soda ash to form borax (the method by which borax was made prior to the discovery of the sodium borate deposits) and the remainder of the process is as before.

The primary borate-producing industry essentially makes and sells boric oxide in some form or other. The actual form is important to the user, i.e. whether sodium or calcium is desirable or deleterious, although there is scope for interchangeability in some applications and this can be influenced by the prevailing relative price and supply situation. This is best exemplified where borate is used as a flux and glass-former in the case of the vitreous industries (glass, pottery glazes, porcelain enamels), which together consume perhaps a third of all borate production. Borosilicate glasses are basically vitreous solutions of silica, boric oxide, lime and soda. When the recipe contains all four, boric oxide may technically be introduced as the free oxide (itself a glass-like substance in appearance), as  $\text{Na}_2\text{O} \cdot 2\text{B}_2\text{O}_3$ , i.e. borax (anhydrous or hydrated), or as colemanite,  $2\text{CaO} \cdot 3\text{B}_2\text{O}_3 \cdot 5\text{H}_2\text{O}$ . For normal borosilicate glass, e.g. 'Pyrex' brand, a sodium borate is usually melted in with the glass batch. This is equally applicable for insulating grades of glass wool. When a soda-free glass is required, which is the case

# RAYMOND THOMPSON

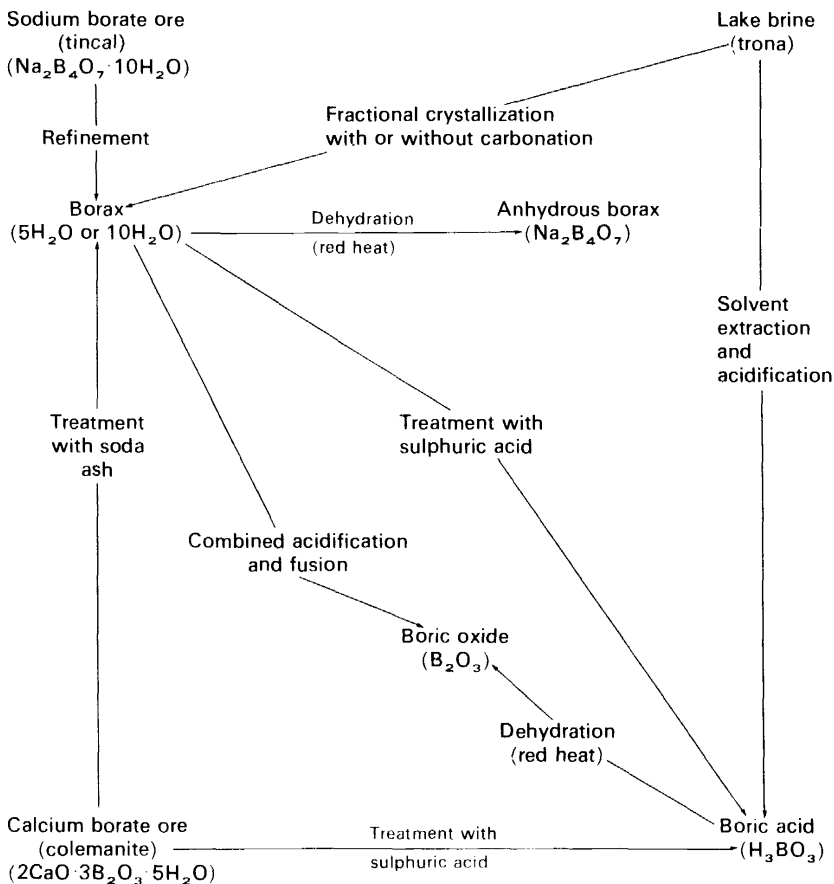


Figure 2. Interrelationship- bulk.

with the production of so-called 'E'-glass for glass fibre textiles and reinforcement for plastics, either boric oxide or cleaned and upgraded colemanite is used. Russian workers are reported to have employed their indigenous sodium borosilicate ores to furnish the three important oxides for vitreous enamel manufacture. Boric oxide is an essential ingredient of good quality vitreous (or 'porcelain') enamels. Many attempts were made in Germany to replace it during World War II, when supplies were cut, but no satisfactory substitute was found and its industry like those elsewhere reverted to borate-based enamels subsequently. The action of boric oxide, a network-former in glass structure (*Figure 3*) is to facilitate the fusion of other oxides, reduce thermal expansion and enhance endurance and brilliance. The same reasons explain its use in pottery glazes, where a high gloss would otherwise be unobtainable without the use of lead oxide (which boric oxide replaced after its prohibition in the early 1900s).

Approximately a further third of total borate consumption is in the washing and detergency industry. This is both as household borax and as

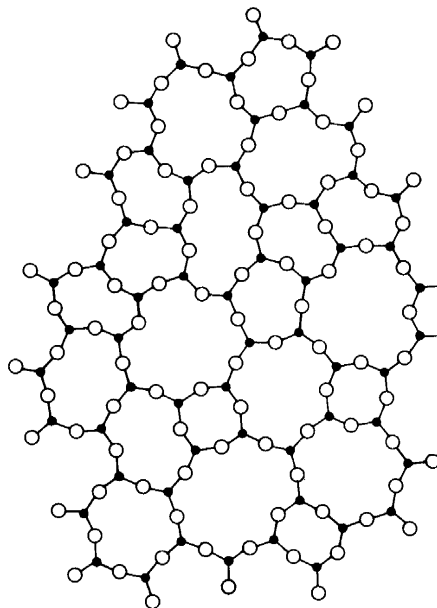


Figure 3. Network.

sodium perborate. It has been customary throughout this century for the American housewife to use borax as an aid to laundering as well as for other applications around the home such as a 'sweetener' in garbage and, in the warmer states, the control of cockroaches (for which borate is a specific stomach poison). 'Twenty Mule Team' borax has been widely sold in retail outlets throughout the USA since the pioneering days of the mule-hauled ten-ton wagons which gave the product its name. The more recent product 'Borateem', which is still largely decahydrate borax but contains additional washing aids such as soil suspenders, bacteriostats and optical whiteners, maintains the tradition. Borax is technically not a water softener and is best described as a mildly alkaline water conditioner which neutralizes acidity, enables soaps and synthetic detergents to work more effectively and solubilizes protein and other natural product stains.

In developed countries other than the USA, where chlorine-based bleaches operating at cool washing temperatures are favoured, sodium perborate is almost the standard bleach for clothes washing. It is present to a level of 20–25 per cent in almost all dry powder washing products, whether soap or syndet based, sold retail in most countries in Western Europe and similar industrialized countries elsewhere. In order to bleach effectively, sodium perborate requires a temperature of at least 50°C; at progressively higher temperatures a lower concentration is effective, or bleaching is faster at the same concentration. Residual sodium borate in the wash water after loss of active oxygen serves much the same purpose as borax does, providing a dual effect.

The remaining one-third of bulk borate consumption is spread over a wide range of applications. There are few manufacturing industries which

do not use it in some form, either in aqueous solution or for its properties in the molten state. In aqueous solution, borax is a very good buffer and also a corrosion inhibitor. It has been standard usage in the USA for many years in automobile coolants, a practice which extended to Europe with the advent of ethylene glycol as an antifreeze. More recently several national railroads have adopted the practice of using it as an inhibitor in diesel locomotive cooling water. Along with boric acid—the mixture being sometimes better than either material alone—it is an important fire retardant for cellulosic materials ranging from cotton to timber. For some such applications, notably the flameproofing of cotton mattresses, boric acid alone is increasingly being specified.

Many wood-boring insects are allergic to borates, and both softwoods and hardwood are preserved by a diffusion-impregnation process known as 'Timborising'. A momentary immersion of unseasoned timber into a hot sodium borate solution is all that is necessary to pick up sufficient liquor which will over several weeks storage diffuse throughout the cross section of sawn timber of dimensions used in the building industry, preserving it for life. Boric acid is only moderately soluble in warm water, but if the ratio is by admixture with borax altered to  $\text{Na}_2\text{O} \cdot 4\text{B}_2\text{O}_3$ , the solubility is trebled. There is no true salt of this composition, but the product (known by the trade names of 'Polybor' and 'Timbor') is made in moderate tonnages by spray drying from an aqueous solution of that ratio. In addition to its enhanced solubility, the material is also of substantially neutral pH.

Smaller but important uses of borax include starch-based adhesives, as a lubricant carrier in wire-drawing and in leather processing. Sodium metaborate,  $\text{Na}_2\text{O} \cdot \text{B}_2\text{O}_3 \cdot 4\text{H}_2\text{O}$  (or  $8\text{H}_2\text{O}$ ) fulfils a need when a more alkaline water-soluble borate is required. It is used in photography and also in adhesives manufacture.

Boron plays an interesting role in agriculture. In relatively high concentration it is phytotoxic, and borax is used as a total-kill herbicide, either alone or in admixture with sodium chlorate (where, in addition to prolonging the effect, the presence of borax prevents the risk of deflagration of dry, dead vegetation). Synthetic organic herbicides have to some extent taken its place in this field. However, one use for which boron can never be replaced is as a trace element in the many plant crops which need it. Boron deficiency in sugar beet causes heart-rot, the yield of sugar being much reduced as a result. Swedes and turnips display a similar deficiency. Without boron, apples and pears develop cork and the fruit is mis-shapen. It is essential for fodder crops such as alfalfa, clover, kale and mustard; and for timber crops such as pines and eucalyptus. The 'beverage' crops, cacao, tea, coffee, grapes and hops all need boron; as do the fibre crops cotton and sisal, and the oil crops coconut, groundnut, olive, rape, sunflower, soyabean and oil palm. Boron is introduced to the crop either along with, or in the manner of, a fertilizer, or as a foliar spray, according to the character of the soil, the rainfall or the nature of the plant. When blended or distributed with the fertilizer, either borax (including the upgraded ore) or colemanite may be used; or, if slower release is necessary, a less water-soluble form such as a borate glass frit. For foliar spraying it is customary to use spray-dried sodium polyborate,  $\text{Na}_2\text{B}_8\text{O}_{13} \cdot 4\text{H}_2\text{O}$ , in order to achieve the maximum solubility in

cold water. The product used for this, called 'Solubor', is compatible with most other foliar feeds.

The largest single use for boric acid is now in the petrochemical industry, for the air oxidation of paraffinic hydrocarbons to the corresponding alcohols and ketones. Based on the Bashkirov reaction, the process is typified by the oxidation of cyclohexane to approximately equimolecular quantities of cyclohexanol and cyclohexanone in order to provide the intermediates for the manufacture of nylon 66. The amounts of boric acid used are stoichiometric rather than catalytic, and a substantial proportion can be recovered for recycle by the hydrolysis of cyclohexanol borate, in which form the alcohol is conveniently separated from the other reaction product. It is in fact the metaboric acid,  $\text{HBO}_2$ , rather than orthoboric acid,  $\text{H}_3\text{BO}_3$ , which is used in the reaction but it is more conveniently formed *in situ* by partial dehydration at about  $165^\circ\text{C}$ . A further use of boric acid in the textile industry is in the manufacture of dyestuffs.

Both boric acid and borax were formerly used widely for medicinal purposes because of their mildly antiseptic nature, but about the only use nowadays in pharmaceuticals is of boric acid in eye lotions.

The solvent properties of borates in the molten state render them valuable in other than the vitreous industries, notably in metallurgy. One of the earliest uses for borax, dating back to pre-Christian times, was as a flux in the refining and joining of metals. Both the boric oxide and soda contents contribute to this characteristic of being able to dissolve other metal oxides. The same qualities are possessed by the mineral colemanite, which has led to its recent large-scale and successful evaluation in the steel-making industry as a flux in partial or total replacement of fluorspar. Its ability to bring the iron ore and lime rapidly into solution, and at the same time avoid the environmentally damaging emission of fluorine compounds, suggests a wide-scale future adoption for the purpose. Another use of borates in the steel industry is for the dry dusting of slabs and billets during hot rolling, the glassy film formed on the hot metal both reducing scale formation and enabling the visualization of flaws.

## MEDIUM TONNAGE PRODUCTS

The quantity of borates of metals other than sodium and calcium consumed by industry is something like two orders of magnitude lower, although exact statistics are equally difficult to obtain. The more important ones are barium metaborate and the zinc borates, of which probably a few thousand tons are made and sold annually. The heavy metal borates are commercially insignificant. Barium metaborate, made from borax and barium sulphide, finds use primarily as a fungistatic pigment for exterior use in geographically limited hot and humid regions, notably in the southeastern states of the USA, where it is customary to paint the outside of houses and other buildings. The mildew-proofing qualities of this slightly water-soluble compound, together with a controlled chalking action of the pigment blend which has a self-cleaning effect, render it unique in relation to performance as well as to geography.

Zinc borate first became established also as a paint pigment, but for fire

retardant purposes. It was the essential ingredient in a US Navy linseed oil-based paint specification during World War II, but thereafter this use lapsed until zinc borates of differing compositions attracted attention as flameproofing additives for plastics during the late 1960s. A particularly suitable composition,  $2\text{ZnO} \cdot 3\text{B}_2\text{O}_3 \cdot 3 \cdot 5\text{H}_2\text{O}$ , which gives rise to the trade name of 'Firebrake' ZB-2335, has been in commercial production for the past few years. It is used mainly along with antimony oxide in chlorinated polymers, e.g. PVC leathercloth for car interior trim and upholstery.

Of the non-metal borates, both ammonium borates and boron phosphate are in routine but limited works-scale production. The former, in highly purified form, is used in the manufacture of electrolytic capacitors. Boron phosphate,  $\text{BPO}_4$ , has been produced commercially at the rate of a few hundred tons annually for the past 25 years, but largely by the petrochemical industry itself for captive use as a heterogeneous catalyst. It is made readily by the co-dehydration of an equimolecular mixture of the parent acids, boric and phosphoric, by heating up to about  $400^\circ\text{C}$ . The product is a white solid of relatively high surface area, useful in the hydration of alkenes and the dehydration of amides to nitriles. If heated to  $1100^\circ\text{C}$ , a water-insoluble crystalline form isomorphous with cristobalite is obtained. Both forms have found limited use in the ceramic industry as fluxes, opacifiers and ingredients of heat-absorbing glasses.

Many esters of boric acid, or 'Boresters', have been made, but their uses are not very extensive largely on account of their hydrolytic instability (although this is partly suppressed in hydrocarbon solution). Many borates are soluble in glycol (some much more so than in water) and condensates containing either sodium or potassium tetraborates, known as 'Liquibors', are used in hydraulic and brake fluids. Several oil companies have sold a boric acid-diol solution as an automobile gasoline additive, while a mixed dioxaborinane is marketed under the name of 'Biobor' as an agent for the control of fungal and bacterial growth in aviation and diesel fuels. The methanol azeotrope of trimethyl orthoborate is employed as a volatile flux in acetylene gas welding, and the  $\text{B}_2\text{O}_3$ -rich methyl metaborate (or trimethoxyboroxine) has found some application in the control of magnesium fires.

The metal fluoborates (sometimes called borofluorides) are used on a scale of several thousand tons per annum. They include potassium fluoborate,  $\text{KBF}_4$ , one of whose applications is in the introduction of boron into aluminium for grain-refining purposes, and the metal fluoborates which find use in the electroplating industry. Boron trifluoride is also made industrially by the relatively inexpensive method of acidification of a boric oxide-fluorspar mixture. It is supplied as the free gas or in the form of complexes or adducts, e.g. with acetic acid, diethyl ether or phenol, and is used mainly as a catalyst in the petrochemical industry. The only other boron halide produced on a factory scale is the trichloride, whose almost sole outlet is in the production of boron filament (see below). It is made by the controlled exothermic chlorination of boron carbide (*Figure 4*), the product, b.pt.  $12^\circ\text{C}$ , being purified by distillation.

The one oxygen-free binary boron compound which is used in moderately high tonnages is boron carbide,  $\text{B}_4\text{C}$ . It is an extremely hard solid, harder



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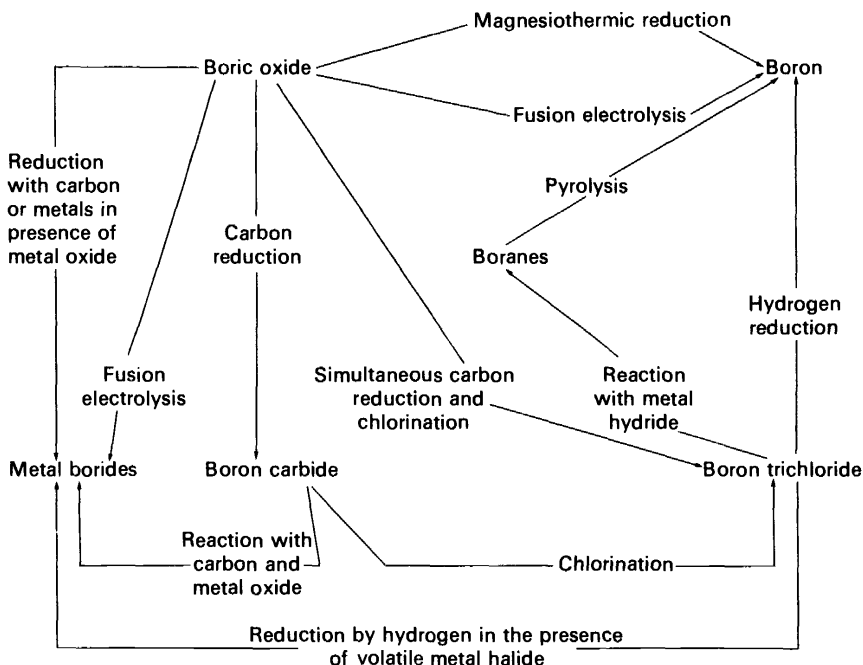


Figure 4. Interrelationship—reduced.

than silicon carbide or tungsten carbide, which has for a long time been used as an abrasive grit. It has too high a melting point ( $2450^{\circ}\text{C}$ ) to be cast readily into artefacts, but by high temperature powder metallurgy (hot pressing) it can be fabricated into simple shapes. Nozzles so prepared are standard items in the shot blasting industry. The same technology is used to press control rods for nuclear reactors. The  $^{10}\text{B}$  isotope, present to about 19.5 per cent in natural boron, has a high capture cross section for thermal neutrons; boron carbide, which contains 78 per cent of boron, is both cheaper and easier to fabricate than the free element. However, the largest single use of boron carbide was a military one, which attained its peak during the Vietnam war. This is as ceramic armour for both personnel and helicopters. The attributes which make it attractive are its light weight (pressed density is about  $2.4\text{g/cm}^3$ ) and the ability to withstand the penetration (albeit with shattering) of armour piercing bullets of calibre up to the thickness of the hot-pressed tiles or monolithic breastplates.

Boron alloys are also produced at the rate of several thousand tons per year, although the boron content of some of them is quite low. Ferroboration, containing about 15 per cent of boron, is probably the most important. Made by the aluminothermic reduction of boric oxide in the presence of iron oxide, it is used mainly to introduce boron into steel. Some of it goes into the production of neutron absorbing steels, which contain around five per cent of boron, but most is used to introduce about 0.002 per cent in order to impart hardenability. Nickel-boron alloys, and to a lesser extent the

mono- and diborides of chromium, are ingredients in welding alloys and hard-facing compositions for the engineering industry. A so-called 'master alloy' or 'hardener' comprising about four per cent of titanium diboride,  $\text{TiB}_2$ , dispersed in aluminium is also made in fairly large quantities and used for the grain refining of aluminium. The boron is usually introduced as potassium fluoborate, which reacts with titanium already present (or added via a titanium salt if necessary) to precipitate the diboride dispersion *in situ*.

## SPECIAL AND DEVELOPMENT PRODUCTS

There are two categories of boron compounds which are sold in low-tonnage quantities but which command a high price for special purposes. They are the refractory binary compounds, and components made therefrom, and sodium borohydride together with its derivatives. Although certain uses are now well-established, both classes are still regarded by their manufacturers as development products for which market growth may be expected to continue.

Elemental boron might perhaps be included in this category also, although to date the industrial demand for it has been disappointingly small and world production over the past few years has probably been under ten tons per annum. There can scarcely be another element whose salts are produced in such large quantities yet whose use in the uncombined form is so small. That which is produced is required mainly for pyrotechnics and as a metallurgical additive, for both of which applications the relatively impure magnesiothermic product 'Moissan' boron is adequate. But an important novel use was developed in the 1960s. This was as a reinforcement filament for plastics and metals. Long recognized as an extremely hard substance, it was found that if boron were deposited in a particular form it was possible to obtain an exceptionally strong fibre which, aided by the low specific gravity of boron, had an unusually high stiffness-to-weight ratio. The favoured manufacturing procedure is vapour-phase deposition from a boron trichloride-hydrogen atmosphere on to a continuous filament of heated tungsten wire. The wire remains in the product as a core, adding marginally to its density. Almost entirely a US development, boron filament has been used in production-run aircraft for wing flaps, rotor drive shafts and rotor blades for helicopters, and for tail components. Selling price is around \$250 per pound.

The inorganic binary interstitial compounds, the metal borides and boron nitride, have received a great deal of research attention since the 1940s, mainly because of the money available to develop materials of their hardness and refractoriness for military and aerospace needs. The wealth of knowledge amassed and published is second only to that on the boranes and related compounds; but in great contrast to these they are materials of exceptionally high physical and chemical stability, properties which technologists have recognized from the basic research and have begun to apply accordingly. Even so the uses are as yet limited, partly by costs. The boride on which most application research has been done, and which is made industrially in the greatest quantity (probably a few score tons per year) is titanium diboride. It is almost the archetype of borides: very high melting point ( $2950^\circ\text{C}$ ), intensely hard (over  $9\frac{1}{2}$  on Moh's scale) and a

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good conductor of heat and electricity (comparable to iron). It is also very resistant to attack by molten metals, entirely inert to aluminium. Boron nitride, which in its relatively soft hexagonal form is analogous to graphite (Figure 5) is also resistant to aluminium attack; but unlike its analogue, although a good conductor of heat, it is a non-conductor of electricity. One of the most interesting and most important applications for both brings  $\text{TiB}_2$  and BN together as a sintered mixture in a hot-pressed ceramic form: boats or crucibles which can be heated resistively to evaporate aluminium in the vacuum metallizing industry. Hexagonal boron nitride also has uses in its own right, particularly where a dielectric but thermally conducting ceramic is required, and taking over from the toxic beryllia-based ceramics. Cubic boron nitride is the analogue of diamond and is of similar hardness. It is made from the hexagonal form at high temperature and very high pressure, and sold industrially under the name 'Borazon' for use as an abrasive.

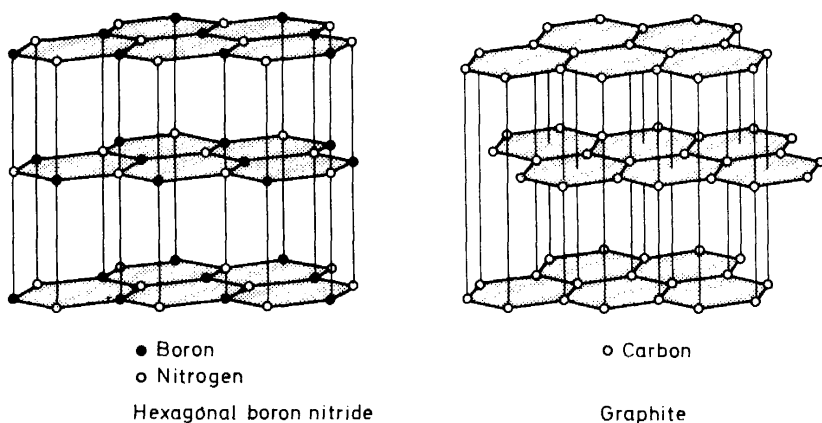


Figure 5. BN and C.

Sodium borohydride,  $\text{NaBH}_4$ , is the only reduced boron compound which has had any semblance of commercial acceptance. It is a powerful reducing agent with useful selective as well as general effect. Much of the stimulus for research into its manufacture and properties came from the US defence programme requirements of the 1940s onwards. It was the important precursor of diborane and the other boron hydrides sought at that time as missile propellants. The favoured production route was the interaction of sodium hydride with trimethyl borate. The reaction was carried out in two steps: first, hydrogenation of a very fine sodium dispersion in mineral oil, followed by reaction with the borate ester at 250–270°C. The product was separated by extraction with liquid ammonia, or alternatively converted into potassium borohydride by precipitation with potassium hydroxide. The process is believed still to be operated on a limited scale by the successors of one of the companies involved in the original development. In addition to its being supplied in solid form, a 12 per cent solution in aqueous alkali is available under the trade name of 'Borol'. Sodium borohydride is employed in small amounts as a reducing agent in organic synthesis, e.g. in the phar-

maceutical industry. Its ability to reduce carbonyl groups selectively is of value also in the bleaching of pulp for the better quality newsprint where yellowing with age is to be avoided. It can also be useful for the prior bleaching of the kaolin filler used along with the pulp; when reacted with sulphur dioxide in alkaline solution, it forms *in situ* sodium hydrosulphite ('hydros'). The economics of so doing are questionable, and it is usually cheaper to use for clay or pulp bleaching either sodium or zinc hydros made by standard routes.

Another field in which large sums of government money were available for research into boron chemistry was in the attempted development of so-called inorganic polymers, a vogue of the late 1950s and early 1960s. The only success reported to date (and this comes long after the termination of large research contracts) has been with a series of carborane-based siloxane polymers known as 'Dexsil'. The products, which have greater thermal stability than wholly organic polymers, are believed to be available in development and small commercial quantities.

### 'LABORATORY CURIOSITIES'

It is perhaps a little unjust to use such a sub-heading above a paragraph which refers to the chemically fascinating boranes and the vast number of related B-H bonded compounds, to which thousands of research chemists have devoted so much of their time during the past few decades. Very much has been learnt about their properties and structures; and indeed, through them, of chemical structure more generally. Nevertheless the harsh truth remains that to industry they are totally irrelevant. That is not to say that the compounds were not produced on a substantial industrial scale in the early days of intercontinental ballistic missiles; but this was military and not commercial production, and was regardless of cost. As far as is known, only laboratory reagent quantities are now made. but doubtless tonnage quantities are held in strategic stockpile.

### FUTURE TRENDS

He is a brave man who tries to make scientific predictions far into the future or, in these uncertain times, industrial and economic forecasts into the relatively near future. Nonetheless, I will attempt to make some regarding the industrial applications of boron compounds.

For the major bulk products it is likely that overall demand will continue to support rates of growth in production similar to those seen in the past few years. This demand will largely be satisfied after the present supply problems in the aftermath of last year's Middle East war, and of temporarily acute local energy shortages, are resolved. The permanently increased cost of fuel, irrespective of availability, is, however, likely to affect the production and use pattern. The supplier industry will be more inclined to concentrate on making the less fuel-intensive products, e.g. low-hydrate borax rather than the fused anhydrous product. The demand for greater thermal insulation in homes and other buildings as a result of higher fuel costs should greatly increase the call for the thermal insulation grades of glass wool, and

hence for the lower cost bulk borates including the upgraded ores. Generally the pattern of use is likely to change as the inevitable increase in borate prices leads some users to use less in their formulations, or to seek substitution. Similarly, other industries will turn more towards borates because they offer a less expensive or more cost-effective alternative to materials now used; or, as with sectors of the glass industry, because their use enables lower fuel consumption. The longer term future trend will be towards the simple borates assuming more the role of premium chemical products than low-cost commodities. The world resource situation will doubtless even demand this next century unless major new deposits are discovered.

The demand for the smaller tonnage borates and fluoborates will probably continue to increase steadily rather than spectacularly. Perhaps a faster relative growth rate can be foreseen for the alloys and refractory boron compounds, and also for sodium borohydride. In an increasingly cost-conscious world it will become progressively more difficult to gain acceptance for new materials unless they can be demonstrated to be more cost-effective than existing ones. For example, excellent though sodium borohydride is as a reducing agent, it will not be used in larger amounts until demands arise for which its performance is unique, or until a breakthrough is achieved in production costs which will enable it to be sold at a price at which it will out-perform in financial terms other reducing agents available. An inorganic polymer similarly will not be used in large quantities until a technical requirement exists which cannot be satisfied by a conventional polymer or by glass. Environmental acceptability will also increasingly be a factor in influencing use patterns.

If cost did not already exclude the acceptance (or even consideration) of boron hydrides for industrial applications, the associated toxicity and explosion hazards would greatly discourage it. Perhaps the boranes are best put into perspective by considering what might seem an absurd parallel, but which is nevertheless as realistic: basing a petrochemical industry on limestone as its sole source of carbon. The products would need to be very special indeed.