THE POTENTIAL DEMAND FOR FERROBORON IN LARGE SCALE APPLICATIONS OF AMORPHOUS METALS FOR TRANSFORMER CORES AND IN OTHER USES.

W. J. ROSENFELDER,

BORAX HOLDINGS LIMITED,
BORAX HOUSE,
CARLISLE PLACE,
LONDON SW1P 1HT, ENGLAND

ABSTRACT

The use of 0.001 to 0.003 per cent B to improve the hardenability of steel has been established practice for over fifty years and has led to an increase in demand for ferroboron in the range of 2000 to 3000 tonnes per annum. Production of ferroboron takes place in a number of countries in conventional aluminothermic plant.

The discovery of the soft magnetic properties of an amorphous iron-silicon alloy containing 3 per cent B, which can reduce the core loss of a distribution transformer to one quarter that of the equivalent grain-oriented silicon system, has led to a potential demand for ferroboron which could rise to some 50,000 tonnes per annum by the mid-1990's. Because an aluminium-free product is required, ferroboron will need to be produced in a submerged arc electric furnace or by the Kawasaki Steel small-scale blast furnace system which produces a 10 per cent B, 13 per cent Si, 0.6 per cent C master alloy.

Recent developments in rapid quenching technology and progress in the evaluation of prototype amorphous metal core transformers are reviewed.

Similar methods of rapid quenching for the production of permanent magnets of neodymium-boron-iron which may replace samarium-cobalt magnets in cars and household appliances, will have a minor effect on ferroboron demand but could lead to a large new requirement for neodymium metal.

INTRODUCTION

The use of amorphous metal in transformer cores in place of grain-oriented silicon steel leads to a reduction of the no-load losses to one quarter. This would result in an energy saving of 15 billion kWh per annum in the U.S.A. alone. Progress in the commercial development specifically of 25 kVA pole transformers is gaining momentum particularly in the U.S.A. and in Japan. We forecast a possible annual demand of 150,000 t.p.a. Fe92 Si5 B3% (by weight) of amorphous metal strip for transformer cores. This would require some 30,000 t.p.a. ferroboron increasing gradually to 50,000 t.p.a. An aluminium-free low carbon ferroboron is required. The need for a reduced price to make the amorphous metal competitive with grain-oriented silicon steel in transformer core construction will put pressure on the ferroalloy industry to manufacture the ferroboron as economically as possible. The submerged arc electrothermal producers of ferroalloys with access to cheap electric power will be in the best position to offer ferroboron to the amorphous metal industry. Kawasaki Stee are developing a blast furnace technique as an alternative to electrothermal reduction.

Other fields of application for rapidly quenched technology such as magnetic heads for tape recorders, brazing alloys, anti-theft devices and rare earth permanent magnets will not provide a significant demand for ferroboron.

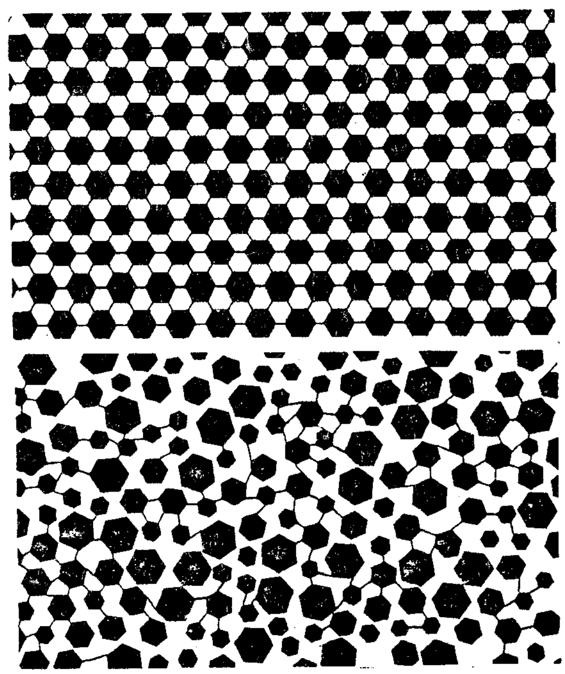
AMORPHOUS METALS

Some twenty-five years ago, studies undertaken at the California Institute of Technology by Prof. P. Duwez (1) and by Miroshnichenko and Salli (2) in the U.S.S.R. showed that by ultra-rapid cooling of specific metallic alloys, an amorphous non-crystalline structure is formed.

This is illustrated in Fig. 1 where the patterned internal structure of normal silicon iron is compared with that of the rapidly quenched amorphous non-crystalline equivalent.

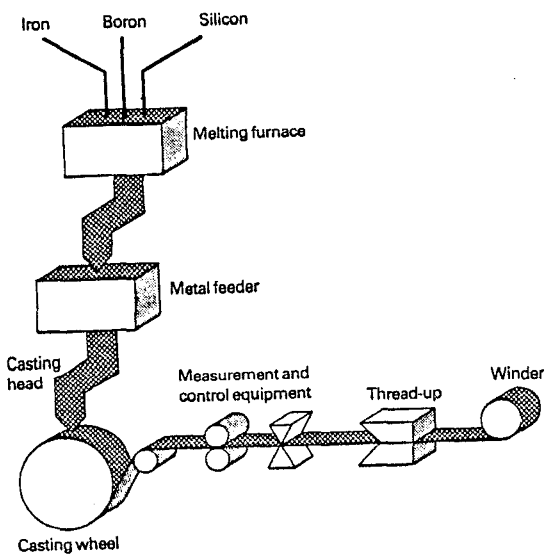
Amorphous Metals (A.M.) cooled to ambient temperature from 1000-1500°C at a rate of one million degrees centigrade per second, lose heat so quickly that their atoms do not have time to form a crystalline pattern.

Fig.1 Regularly patterned internal structure of normal silicon-iron (top) and amorphous non-crystalline silicon-iron (bottom)



By 1969, (3) the technique of producing long lengths of ribbon by planar flow casting was perfected. Fig.2 shows how an iron-boron-silicon alloy is melted in a furnace and fed to a crucible usually made of quartz or silicon nitride and then cast onto a water cooled drum which is rotating at a speed of 60 miles per hour. Copper or beryllium copper are most commonly used for the rotating wheel. The strip can be cast up to 17 cm. wide and 0.03 mm. thick. It is wound onto a reel ready for shipment.

Fig 2. Casting amorphous metal strip



Many thousands of compositions have been studied. The most important, from an industrial point of view, is the 92%Fe 5%Si 3%B (by weight) alloy which has superb magnetic properties making it an ideal material for the core of transformers. There is no doubt it will eventually replace most of the 3% silicon grain-oriented steel now in use.

Before considering the use of amorphous metal in transformer cores, we can compare the manufacturing technology required to produce grain-oriented silicon steel by casting, re-heating, hot and cold rolling etc. with the single stage planar flow casting which goes straight to the thin A.M. ribbon. Table 1 sets out these two processes :

Table 1

Transformer

Core Material Manufacturing Processes

Regular Grain Oriented Silicon Iron	Amorphous Metal
MELT	MELT
Cast Reheat Hot Roll Pickling Cold Roll Anneal Cold Roll Decarb	Cast
COAT Hi-Temp Anneal Insulate	COAT Magnetic Anneal
Test	Test

One problem is that grain-oriented silicon steel is normally rolled down to a thickness of 0.3mm. whereas for rapid quenching a thickness of the ribbon is usually 0.03 mm. to achieve an amorphous structure. This rather brittle thin ribbon requires special techniques for handling. It can be used as such for the production of core wound transformers.

However, the Allied Corporation, the leading company in the field who have manufactured amorphous metal strip at Parsippany, New Jersey since 1981 (4), has now perfected a process of applying pressure and temperature to as many as 8 layers of amorphous metal ribbon to produce an 0.24 mm. thick strip (5).

This POWERCORE has a pack factor of 90% getting close to the 96% achieved with grain-oriented silicon steel. This is a great improvement on the 80% for A.M. thin ribbon. The way is thus open to using POWERCORE in stack transformers so that entry into the larger power transformer application is facilitated.

THE USE OF A.M. IN THE TRANSFORMER INDUSTRY

The fine electrical industry has found a series of uses for A.M. in such applications as magnetic heads for tape recorders, ground fault interrupter switches, anti-theft devices. None of these require substantial quantities of raw materials.

We should like therefore to concentrate on progress in the use of A.M. in the transformer field which could have a profound effect on the ferro-alloy industry specifically the medium scale production of ferroboron.

U.S.A.

In 1978, after three years of detailed study, the U.S. Electric Power Research Institute (E.P.R.I.) began the award of the following contracts :

(1) Allied Corporation, METGLAS Products, Parsippany, New Jersey.

A five year programme was sponsored at a cost of $8 million to develop an economic process for the manufacture of amorphous metal strip (the Allied trademark for which is METGLAS).

The target price for large quantities at that time was $3.30 per kg. but now this has been reduced to $2.20 per kg. for Fe92 Si5 B3% A.M. to be competitive with grain-oriented 3% silicon steel.

Allied's $10 million plant at Parsippany, N.J., has a potential capacity of 10,000 t.p.a. and might be able to approach the target price level when it can be operated at a level approaching full output.

(2) Westinghouse Electric Corporation, Sharon, Pennsylvania.

The grant of $1.2 million was awarded for Westinghouse to design, build and evaluate stack laminated power transformer cores.

Harry R. Sheppard, with Edward T. Norton of E.P.R.I., reported their results at the Fifth International Conference on Rapidly Quenched Materials at Wurzburg Sept. 7th 1984 (6).

They evaluated the total owning cost of amorphous metal for a power transformer core with that of grain-oriented silicon steel. By total owning cost they included the purchase price of the transformer together with the present worth of the cost of losses incurred by the transformer throughout its life.

In addition, Westinghouse have also worked on distribution transformers. They announced the shipment of the first 200 amorphous core overhead 25kVA distribution transformers to San Diego Gas and Electric Co. at the end of 1985. These are showing a no load loss of only 20 watts. Westinghouse have commitments from U.S. utilities for over 1000 amorphous units to be delivered during 1986.

(3) General Electric Corporation Corporate Research, Schnectady, N.Y. and Distribution Transformer Dept. Hickory, N.C.

In 1978-1981, G.E. built up experience first in producing small ½ and 1 kVA transformers followed by three 25 kVA units. One of these was installed by the Duke Power Company as early as April 13, 1982 and core losses and performance have been checked periodically.

In January 1983, G.E., under a $5 million E.P.R.I. contract, began the construction of 25 pre-prototype 25 kVA A.M. transformers for field evaluation. These were installed in 25 different utilities through the U.S.A. and tests at six monthly intervals have shown excellent performance.

Under the E.P.R.I. contract, a further 1000 25 kVA A.M. transformers were constructed in late 1985 and these are now in operation.

An indication of the core loss improvement is given in the following Table 2 :

Table 2
Performance of Amorphous Metal and Silicon Steel Transformers
25kVA 7200/12470Y - 120/240

	Amorphous Metal	Silicon Steel (HE)
Core Loss	28 W	86 W
Exciting Current	0.3%	0.9%
Audio Noise	38 db	48 db(Limit)
TIF 100%/110%	3/14	22/66(Limit)
Short Circuit	Passed (Full33X)	Passed (40X)
In-Rush Magnetizing Current 0.01 Sec/0.1 Sec.	17/8	25/12
Impulse LV & HV	Passed	Passed

The Unit passed all industry Standard Tests without any change in Core Performance

JAPAN

As in the U.S.A. and in Canada, Japan is a country where the small single phase pole transformer located outside the home is in common use.

The Osaka Transformer Co. began their studies on amorphous metal in 1979 and have by now gained experience in producing 10 kVA, 20 kVA and 30 kVA transformers. In Y. Yamamoto's paper at Wurzburg (6, p.1629) he compares the no-load loss of METGLAS SC which contains some 0.5% carbon with the METGLAS S2 which is carbon-free.

Table 3
Comparison of METGLAS 2605SC and METGLAS 2605S2 with silicon steel currently in use.

	ITEMS	METGLAS 2605SC	METGLAS 2605S2	SILICON STEEL Z-6H
Electromagnetic characteristics	No-load loss [W/kg] at 100°C, 1.4 T/60 Hz	0.27*	0.21*	0.9 *
	Magnetizing force [VA/kg] at 100°C, 1.4 T/60 Hz	0.72*	0.37*	0.94*
	Saturated flux density [T] at 25°C / at 100°C	1.61* / 1.51*	1.55* / 1.49*	2.03 / 2.03
	Coercive force [Oe]	0.06	0.04	
	Magnetostriction	Larger		Smaller
	Specific resistance [μΩ-cm]	125	130	45
Physical Characteristics	Thickness [μm]	30	30	300
	Specific gravity	7.32	7.18	7.65
	Space factor [%]	> 75	> 75	97

*Value taken from the characteristic curve.

Note: Every characteristic value of METGLAS 2605SC and METGLAS 2605S2 is an average value and that of silicon steel Z-6H is shown as typical example.

You will see METGLAS 2605 S2 gives an even better no-load loss of 0.21 W/kg compared with 0.27 W/kg for the carbon containing METGLAS 2605 SC. Both of these are far superior to the 0.9 W/kg loss with grain-oriented silicon steel.

Testing of these transformers is proceeding at Chugoku, Shikoku and Kyushu Electric Power companies.

In addition, Tokyo Electric Power Co. and the Japanese Central Electric Power Research Institute commissioned Toshiba Corporation, Hitachi Ltd. and Takaoka Co. to fabricate A.M. transformers for field testing.

EUROPE

The G.E.C. Distribution Transformers Ltd. Broadstairs, U.K. (7 & 8) has reported on two prototype transformers they built for evaluation by the Central Electricity Generating Board.

In general, in Europe the pole transformer is rarely used so it will be necessary to use the technology developed for building stack transformers from multilayers of amorphous metal.

COMMERCIAL CONSIDERATIONS

In the U.S.A. alone, 40 million distribution transformers of all types now lose 35 billion kWH annually. Replacement with amorphous core transformers could mean a saving of 23 billion kWH or $1.2 billion annually.

Of these, about 25 million transformers are the 25 kVA pole transformers which have a core weight of about 100 kg. each.

Replacement of these alone by amorphous metal core transformers would save 15 billion kWH annually worth $700 million (5, p.1626).

Approximately 1 million pole transformers, are replaced every year so the demand for amorphous metal could reach 100,000 tonnes per annum.

This assumes a 25-year programme for the total replacement of grain-oriented silicon steel pole transformers by amorphous metal. This would mean a substitution of a part of the present 400,000 tonnes grain-oriented silicon steel usage in the U.S. transformer industry.

In Japan, there are eight million pole transformers installed with replacement after a 20-30 year life and some expansion of the electricity supply network. That is, an annual demand for 400,000 units which at 100 kg. core weight, means a requirement of 40,000 tonnes A.M. per annum if a total replacement of grain-oriented silicon steel by A.M. comes about. The Tokyo Electric Power Co., the largest and most influential of the nine Japanese power companies, requires 75,000 new units a year to replace those of their 1.5 million pole transformers which have reached the end of their useful life. Their full in depth study on amorphous metal, announced in 1984 (9) should be complete by late 1988.

Progress in Canada, where power is cheap, and in Europe, where transformers are large and more difficult to construct with A.M., may be slower. We can surmise potential annual demand could be as follows :

Table 4

	Annual requirement Tonnes A.M. core
U.S.A.	100,000
Japan	40,000
Europe, Canada	10,000
	150,000

If this level of usage were to be achieved by 1992 and thereafter China, India and Australia etc. come into the picture, one can postulate the following requirements for distribution and eventually power transformers.

Table 5

	Amorphous Metal 3%B 5%Si 92%Fe	Ferroboron 15%B
	Tonnes	
1986	1,000	200
1988	10,000	2,000
1990	100,000	20,000
1992	150,000	30,000
1994	200,000	40,000
1996	250,000	50,000

PERMANENT MAGNETS

One other area of interest to the ferroboron producer, is the widespread activity in neodymium-boron-iron magnets for starters for motor cars and domestic appliances. The cost/performance could be superior to that of samarium-cobalt now in use. The annual requirement for samarium-cobalt is 240 tonnes and is expanding rapidly. Partial replacement by Nd-Fe-B is possible. Inroads into the Alnico (8000 t.p.a.) and ferrite (98,000 t.p.a.) markets may take place if neodymium metal can be produced cheaply. Jacobson and Evans of G.E.C. reviewed this subject in depth (14). C. Herget of Th. Goldschmidt (15) gives the following comparison for the two most important compositions :

	Chemical composition by weight		
	Nd	Fe	B
$Nd_2 Fe_{14} B$	26.68	72.32	1
$Nd_{15} Fe_{77} B_8$	33.03	65.65	1.32

Sumitomo Special Metals are working on powder metallurgical techniques for their NEOMAX magnets whereas General Motors are using rapid quenching to produce the powder for resin bonding to manufacture their magnet sold under the name of MAGNEQUENCH.

The second composition is the more important but at 1.32%B, the quantity of ferroboron required will be small. General Motors announced in March 1985 an investment of $68 million in a MAGNEQUENCH plant (16) to be in production later this year.

The most optimistic estimate of demand might be :

Year	Nd-Fe-B	B at 1.32%	FeB (15%B)
1990	2,000	26.4	176
1995	8,000	105.6	704

For this application, the level of aluminium is not critical so either aluminothermic or carbothermic ferroboron can be used. This sector is thus insignificant as a consumer of ferroboron in comparison with the much larger potential demand from the transformer industry. For the rare earth industry, it does however represen a major new use for neodymium metal.

THE FERROBORON INDUSTRY

The use of boron to improve the hardenability of steel, first introduced in the 1930's, has shown steady growth but to avoid excessive brittleness, the level of addition is normally well below 100 ppm (10). The most common product used is ferroboron. Annual demand from the steel sector does not exceed 3000 tonnes ferroboron. A number of well known ferro-alloy producers such as London and Scandinavian Metallurgical Co. (L.S.M.), G.F.E., Murex, Treibacher Chemische Werke, Pechiney Metallurgie, Taiyo Mining, N.K.K., operate aluminothermic plants to make ferroboron giving a product containing 15-20%B, 2% Al and 0.5% Si (11). For amorphous metals, the ferroboron must be free of aluminium so a carbothermic process has been developed not only for ferroboron but also for nickel and cobalt boron which find application in speciality amorphous metals with improved magnetic properties.

The first suppliers of high purity submerged arc electric furnace produced ferroboron were L.S.M. in the U.K., Elkem Inc., Niagara Falls in the U.S.A. and Mitsui Mining in Japan. Mitsui Mining have concentrated on ultra-pure FeB, Co B and NiB as can be seen from Table 6 :

Table 6

Typical Analyses of Fe -B, Co- B and Ni - B

	Fe	Co	Ni	B	Al	C	Si	Mn	Mg	P	Cu
Fe- B	82.1	-	-	15.7	0.05 0.08 0.01	0.20	0.86	0.07	-	0.021	0.002
Co- B	0.45	81.9	0.14	15.6	0.04	0.07	0.70	0.06	0.01	0.022	0.009
Ni- B	0.70	0.25	82.0	15.2	0.05	0.18	0.95	0.05	0.01	0.000	0.009

Form: lump 4 - 20, 20 - 50 mm

powder + 200 mesh <1%

- 200 + 350 mesh 15%

- 350 mesh 85%

Mitsui Mining & Smelting Co., Ltd.

Reasonable prices can be obtained from the electronic industry but the quantities required are limited.

Both L.S.M. and Elkem can meet the requirements on quality of the large scale amorphous metal producers of whom Allied METGLAS Products at Parsippany, N.J. are the most important. There is a complex patent position. Allied have tried to prevent importation of amorphous metal into the U.S.A. through the U.S. International Trade Commission. In Japan, Allied formed a joint company with the Mitsui group called NAMCO and they have also set up an European Sales office in Brussels. Other organisations including Nippon Steel, Kawasaki Steel, Hitachi, Unitika (Japan), Enka (Holland), Vacuumschmelze (Germany), G.E.C.-INCO (U.K.) have study programmes. Where possible, they also have production units operating outside the Allied patents. They may become substantial consumers of ferroboron in due course.

Kawasaki Steel have a different approach to aluminium-free ferroboron production. They have built a pilot plant to produce an alloy of about 10% B 13%Si 0.6%C 76.4% Fe (by weight) by a carbothermic blast furnace technique. This is ideally suited to countries such as Japan where electric power is expensive so that electric arc furnace processes are becoming uncompetitive. The reduction of the carbon content to 0.6% in the Kawasaki Steel process is a major achievement. Further details can be learnt from their two U.S. patents 4,397,691 and 4,505,745 issued in 1983 and 1985 respectively (12) (13).

Additionally, there are three other Japanese suppliers of carbothermic FeB with the following plant capacity :

Nihon Denko (1900 t.p.a.)
J.M.C. (2000 t.p.a.)
and Yahagi Iron Co. (500 t.p.a.)

All use submerged arc electric furnaces with design improvements.

G.F.E., the German associates of L.S.M., have cheap power at Weissweiler and Elkem have widespread resources in West Virginia, Canada, Norway and Iceland. Any of these could be used for ferroboron production.

However, there is a risk of cross-contamination if ferroboron is produced on a campaign basis, in large furnaces intermittently with other ferro alloys. Even if the demand for ferroboron does reach 50,000 t.p.a. over the next decade, this is a small quantity by the standards of the ferro alloy industry. Hence, fragmentation of the market among too many suppliers may make it difficult for any of them to achieve and sustain a $2.20 per kg. FeB (15%B) price. This is considered necessary to produce amorphous metal which, in turn, needs to be sold at $2.20 per kg.

Eventually, two or three leading producers of ferro alloys will specialise in ferroboron production.

The view expressed by the transformer manufacturers is that there is a limit to the premium they can accept for amorphous metal over the price of grain-oriented silicon steel. However, the total present worth of the saving in power losses over the life of the transformer is subject not only to power costs but also to financial considerations which are difficult to predict. Thus the erosion of the A.M. to grain-oriented silicon steel price ratio required (caused, in part, by the improvement in the performance of grain-oriented silicon steel) from 2:1 down towards 1:1 is causing a serious problem for the amorphous metal producer. They, in turn, are bringing pressure to bear on the ferroboron manufacturer to bring down his price estimate for the supply of multi-thousand tonne quantities.

BORIC ACID FOR FERROBORON PRODUCTION

Boric acid contains 17.48%B so that 1.07 kg. is required per kg. FeB (15%B) on the basis of a yield in ferroboron production of 80%. Hence the cost of boric acid at 66 cents per kg. i.e. 71 cents per kg. FeB is a not insignificant factor in the cost of producing FeB. Boric acid prices should remain stable over the foreseeable future.

Fortunately there is adequate spare capacity for boric acid manufacture to meet the full requirements of ferroboron for amorphous metal production.

Table 7

Annual Capacity

	Short tons
U.S. Borax	200,000
Borax Francais	55,000
Larderello	50,000
Kerr-McGee Chemicals	35,000
Etibank	35,000
Other producers, U.K., Spain, China, Argentina	25,000
	400,000

(225,000 s. tons B_2O_3)

The boric acid operation of our own group company, U.S. Borax at Boron, California, is a modern highly efficient unit that converts sodium borate minerals directly to boric acid at the mine site. Expansion of production capacity could be installed rapidly should the amorphous metal distribution transformer project take off in the period 1988-1996. Similarly our 55,000 t.p.a. plant at Coudekerque, France, which uses Turkish colemanite, could be enlarged and the Etibank have plans to increase production in their own boric acid operations in Turkey as the market situation improves.

The Chilean Government project at the Salar de Atacama to co-produce potassium chloride and sulphate with lithium chemicals and a possible 30,000 t.p.a. boric acid could become a reality by the late 1990's.

Thus even if traditional uses of boric acid in borosilicate glass and glass fiber, ceramics, cellulose insulation etc. grow rapidly there is ample capacity for boric acid production to meet even the most optimistic forecast of amorphous metal demand.

We can conclude by saying low cost ferroboron will be required by the amorphous metal industry but the quantity will never become large in the context of the ferro alloy industry.

References

(1) W. Klement, R.H.Willens and P. Duwez, Nature, 187 (1960) p.869.

(2) I.S. Miroshnichenko I.S. and I.V. Salli Ind. Lab. 25 (1959)p.1463, Zav. Lab. 25 (1959)p.1298

(3) R. Pond, R. Maddin paper presented at TMS-AIME, 245 (1969)p.2475.

(4) Walter J. Rosenfelder"A Review of the Activities of the Major Industrial Groups in the Field of Rapidly Quenched Materials with Specific Reference to their Future Requirements of Boron" paper presented at Rapidly Solidified Materials A.S.M. Conference, San Diego, 3-5 Feb. 1986,pp.427-434.

(5) D. Raybould, A.C. Diebold "An investigation by Auger and laser acoustic microscopy of the bond between layers of consolidated amorphous ribbon (POWERCORE), Journal of Materials Science, 21 (1986) pp.193-202.

(6) Harry R. Sheppard, Edward T. Norton "Amorphous Metal Core Power Transformers (Economic considerations pp.1647-1652 in Rapidly Quenched Materials, S. Steeb, H. Warlimont ed; Proceedings of 5th Int. Conf. RQM, Wurzburg, Germany 1984.

(7) K. Frewin, "Amorphous metal cores", Electrical Review, 214 (20) (1984) pp. 23 & 26.

(8) K. Frewin, "Amorphous Materials in Distribution Transformers" paper presented at Soft Magnetic Materials European Physical Society Conference Blackpool, England, August 1985.

(9) Nikkei Sangyo, Tokyo, November 19, 1984.

(10) Boron in Steel, S.K. Banerji and J.E. Morral ed; AIME, Milwaukee, Wisconsin, 1979.

(11) R. Hahn, H-J Retelsdorf "Production and use of ferro-boron-alloys" pp. 49-55"Nd-Fe Permanent Magnets - Their Present and Future Applications" I.V. Mitchell ed; Commission of the European Communities, Brussels, 1984.

(12) T. Hamada, N. Tsuchiya, T. Inatari, Y. Takada, M. Sumito, E. Katayama, T. Koitabashi, K. Okabe, Y. Ito, "Method for producing Fe-B molten metal", U.S. Patent 4,397,691 (1983).

(13) T. Hamada, N. Tsuchiya, Y. Ito, T. Inatari, Y. Takada, M. Sumito, T. Koitabashi, H. Katayama "Methods of producing and using amorphous mother alloy", U.S. Patent 4,505,745 (1985).

(14) D. M. Jacobson, D. S. Evans, "Possible takeover by neodymium alloy supermagnets" Magnetic Materials, (1985) pp.667-674.

(15) C. Herget, "Metallurgical Ways to NdFeB Alloys. Permanent Magnets from Co-Reduced NdFeB", paper presented at 8th Int. Workshop on Rare-Earth Magnets and their Applications, Dayton, Ohio, May 1985.

(16) E & M. Journal, (March 1985), pp.127-128.