THE FUTURE OF LOW TEMPERATURE NIOBIUM BASED SUPERCONDUCTORS

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Abstract

A prior study on Niobium consumption presented at the 1981 Proceedings of the International Symposium is compared to the actuality of the current use of Niobium based superconductors. Lesson's from these projections are used along with current market and technology trends to project Niobium usage for 2011. Applications and present markets are reviewed to bring depth to these projections. The impact of new High Temperature Superconductors (HTS) is also discussed and considered as to its impact on Niobium based superconductors.

Introduction

Niobium has been a key element and major player in superconductivity ever since the discovery of niobium based superconductors in 1954. Predicting niobium's future growth is a challenging task especially with the uncertainty that a whole new class of high temperature superconductors (HTS) adds to the future. HTS materials first discovered by Bednorz and Muller in 1986 (1) now have critical temperature as high as 134 K. To complicate the issue further is the discovery of another new material MgB_2 in 2001 with a critical temperature (T_c) of 39.4 K, a relatively simple structure and three-dimensional superconductivity such as in low temperature superconductors (2). A key question is the effect of competition of HTS conductors on niobium based superconductors in five to ten years, the likely maturation cycle of these materials.

This paper will attempt to predict the future by first evaluating the past, looking at the present both in LTS and HTS and then project the future based on current market and technological considerations.

The Past - 1981

To begin to build a basis for prediction and extrapolation a brief review of niobium based superconductors as described in "Niobium Proceedings of the International Symposium "in 1981 is instructive. The commercial superconductors were NbTi, Nb_3Sn tape, and bronze based Nb_3Sn. Efforts were being made to produce Nb_3Sn by other processes such as the powder in tube being developed by the Dutch and tin infiltration of niobium powder. NbTi conductors had as many as 2100 filaments while Nb_3Sn had 2800 or more through double extrusion technique (3). The wires were in many configurations including braids; cables, monoliths and hollow configurations designed to suit the various applications (4). Many materials were under development including Nb_3Al; Nb_3Ge, NbN as well as non-Nb based materials such as V_3Ga and C15 materials such as V_2Hf (4).

The applications utilizing superconductors was very much driven by government programs. The so called "energy crisis" and the resulting search for energy independence were at the heart of many programs. Superconductors offered promise to be part of cost effective solutions to new energy technologies such as Fusion and MHD as well as ways to improve the energy efficiency of existing methods of energy generation. Only power generation competed with existing materials. In all the other applications superconductors enabled the feasibility. Table I summarizes some of the major programs then underway.

Table II, from H. Stewart paper at the symposium in 1981 lists seven more applications and gives volume estimates for two time frames (5). It will be interesting to compare later the latest projections and evaluate how many applications are still under consideration. What is most interesting is that the major commercial application and large-scale user of niobium MRI was identified using the old name NMR that was used both for imaging and laboratory analysis as a major application. What is equally interesting is that Furuto speculated about the possibility of LN_2 superconductors beginning in 1982, 5 years ahead of the actual discovery (4).

Table I Major applications of superconductors

Application	Projects	Comments
High Energy Physics (Fundamental Research)	Fermi Tevatron USA, HERA Germany, Isabelle USA	Isabelle abandoned for ill fated SSC
Magnetic Fusion (Energy crisis driven)	T15 Russia, Tor Supra France, LCT, MFTF , USA	MFTF completed and magnets tested but never used.
Magneto Hydrodynamics (MHD) (Energy Crisis)	CDIF - 5T USA	Increased energy efficiency as a topping cycle for coal burning plant.
Generators (Energy crisis driven)	EPRI/Westinghouse 300 MVA US, Japan, Russia, France, Germany, Italy, Switzerland	20 MVA built by GE, 5 MVA Westinghouse
Energy Storage (Energy crisis driven)	LASL 30 MJ USA, EPRI/DOE diurnal storage	LASL coil tested on grid. Diurnal storage concept never executed
Magnetic Levitation (High speed rail transportation)	JNR Japan, Germany	Ongoing, scaled up to 18.4-km test track
Magnetic Separation	US, UK, Germany	Only commercial application

Table II Projections made in 1981 for high purity niobium consumption for superconductors (5)

Application	1981-1985	1986-2000
NMR and Lab Magnets	23	175
HEP	40	80
Fusion	20	230
Magnetic Separation	1	2
SMES	4	16
MHD	5	50
Levitated Trains	0	16
Generators	1	11
Computers & Instrumentation, Ship Propulsion, Power Transmission, Current Limiter, Gyrotrons, Isotope Separation, Defense	10	158
Total tonnes - assumed 50% yield	103	737

The Present -2001

To build an understanding of niobium in superconductivity today it would be best to first briefly review the state of the art in commercial niobium based superconductors and then review the current applications.

Only two niobium based systems have been commercialized, NbTi and Nb_3Sn. Nb_3Al is still under development for specialized applications such as high radiation or superior strain tolerance. NbTi is the industrial workhorse used for fields usually below 9T at 4.2K and is fabricated in much the same way by all manufacturers. Key to its success even though it has a critical temperature of 9.2K roughly half that of Nb_3Sn is its ease of fabrication and robustness in application. As a ductile material with relatively high strength it winds well into magnets which are essentially pressure vessels for the magnetic field they generate. In addition costs of conductor have continued to improve through a combination of current density improvement and economies of scale. The development that ensued for the ill-fated SSC program had a very significant and positive impact on the overall measurement of performance, $/kilo Ampere meter ($/kAm) of these conductors. Figure 1 is a self-explanatory outline of this process for NbTi.

Two key factors contributed to the improvement of performance over 1981; highly homogeneous alloy and the incorporation of a Nb diffusion barriers about the NbTi to prevent the formation of intermetallics. Conductors today achieve current densities in the alloy of 3000 Amps/mm^2 at 5 Tesla, a typical MRI peak field 50% better than 1981 conductors made for the Fermi Tevatron (6).

The conductor being manufactured for the Large Hadron Collider (LHC) at CERN can best illustrate the state of the art in NbTi. These conductors are far more sophisticated than current MRI conductors are but certainly techniques employed will find their way into improving current MRI conductors.

For high field application usually above 9 T multifilament Nb_3Sn is used though GE Medical Systems has used Nb_3Sn tape for open MRI system, as discussed in more detail later. Production today of Nb_3Sn is by the bronze process with improvements and an new process, "internal tin" embodied in various configurations. The bronze process is mainly used for high field NMR magnets. Internal tin is superior in current density, as the tin is not limited to the 13-wt% typical of bronze-based conductors. This allows the volume fractions of Nb_3Sn to be significantly higher than the bronze process thereby offering typically twice the current density of bronze conductor (7). The conductor is also easier and less expensive to fabricate as repeated anneals required in bronze base conductors, typically every 50 to 60% in reduction are not required. Internal tin is finding greater use in fusion programs such as ITER and high field magnets as well. Figure 4 is an outline of the typical stages of manufacture in an internal tin conductor. Figure 5 is an internal tin conductor with a copper stabilizer, 19 bundles of niobium filaments, a tantalum diffusion barrier and cores of tin prior to reaction.

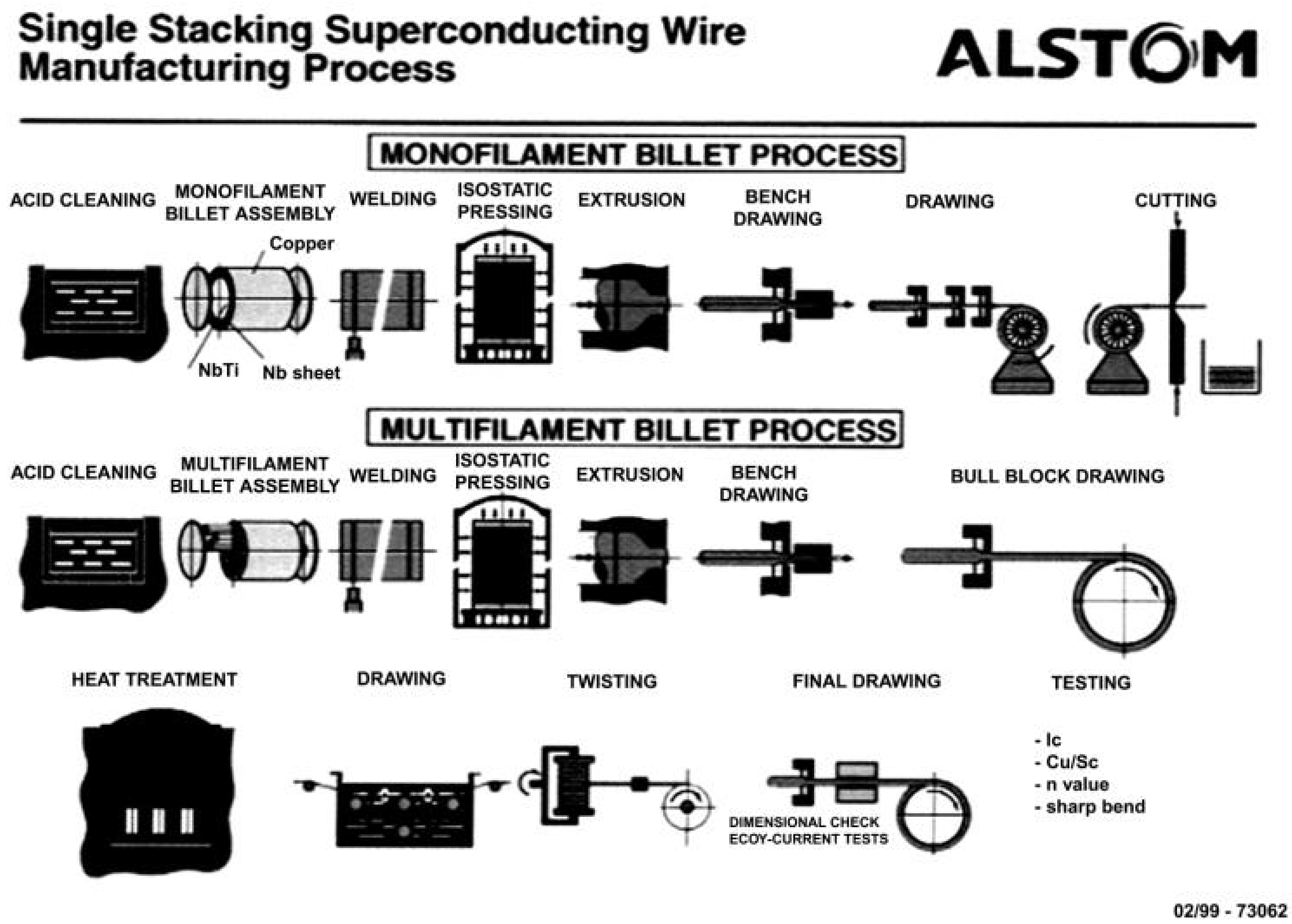

Figure 1: Outline of manufacture for a modern NbTi superconductor courtesy of Alsthom.

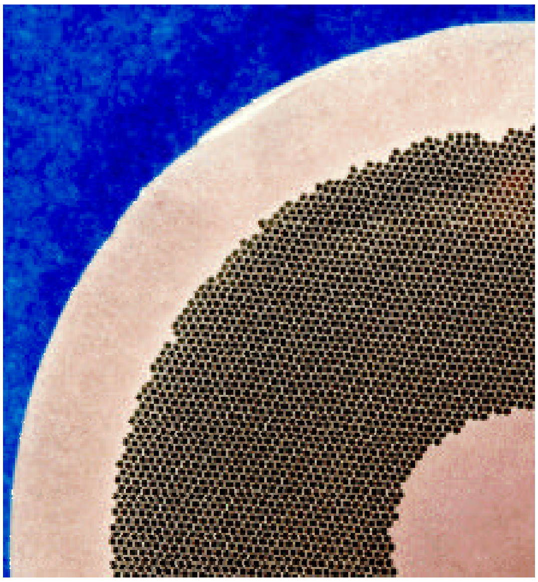

Figure 2: Alsthom LHC conductor with 8900 7-micron filaments in a 1.065mm wire with a 1.6 /1 copper to superconductor ratio.

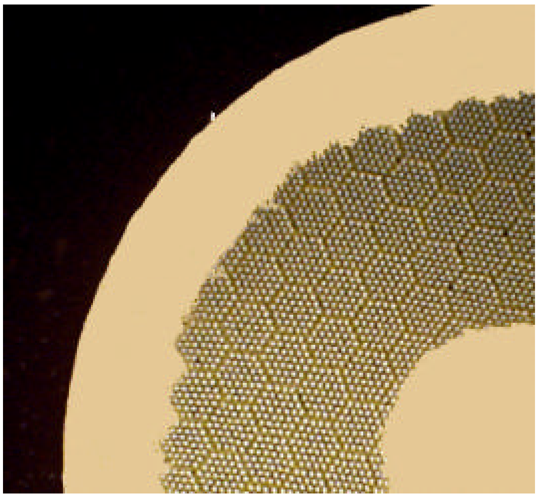

Figure 3: IGC-AS conductor for LHC using a hex cell stacking approach.

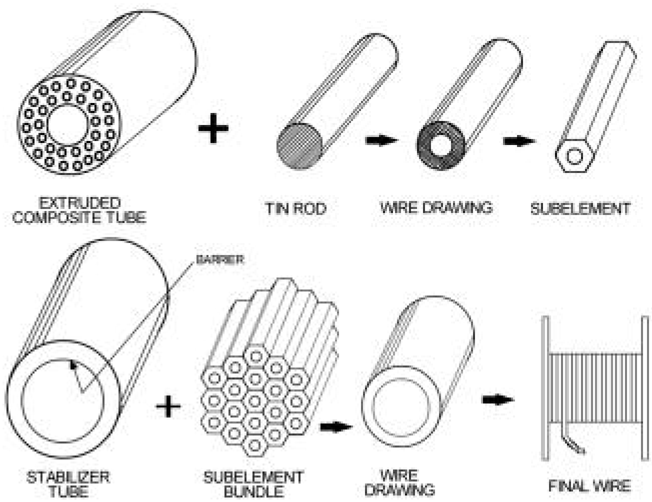

Figure 4: Process outline of an internal TiN conductor as practiced by IGC-AS.

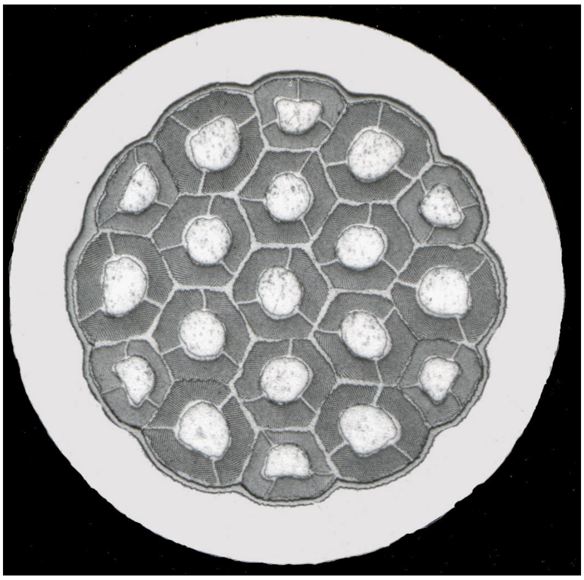

Figure 5: IGC-AS Internal Tin conductor with a Ta diffusion barrier.

Market and Applications - 2001

The present market for niobium based superconductors can be divided into commercial based and project based systems.

Commercial Applications

The commercial segment is presently composed of MRI, NMR, FTICR, research magnets and Magnetic Separation.

MRI is by far the largest with over 2000 units being produced per year and an estimated installed base of 12000 (8). MRI systems have continued to come down in total cost of ownership while offering improved performance and an expanding range of application. For example, from 1994 to 1999 prices of a 1.5T actively shielded magnet were reduced by 40% (8). A typical 1.5 T self-shielded magnet manufactured by IGC for Philips Medical systems is illustrated in figure 6. The introduction of self-shielded magnets has substantially increased the superconducting content.

NMR - NMR magnets have become an essential tool for almost any analytical laboratory. The explosion in bimolecular research has continued to expand the market for these systems. The leading manufacturer of NMR magnet systems, Oxford Instruments has over 4500 magnets installed worldwide. Based on a roughly 50% market share this implies over 9000 systems worldwide (9). It is estimated that yearly consumption of Nb in both NbTi and Nb_3Sn is about 15 tonne (10). NMR and Research magnets are currently the main commercial markets for Nb_3Sn. An example of a state of the art 21.1T 900 MHz NMR magnet manufactured by Oxford Instruments is illustrated in figure 6. Note most systems are significantly smaller.

Fourier Transform Mass Spectroscopy -FT/MS is another growing application driven by needs for fast analysis of complex molecules in the biotechnology industry. Magnets are similar in overall size to MRI with smaller bores but usually are rated at fields from 3 to 12 T. Hence these are much more material intensive than MRI. Higher fields allow larger molecules such as proteins and enzymes to be analyzed. Approximately 250 systems have been installed worldwide (11).

Figure 6: IGC 1.5T active shielded MRI magnet.

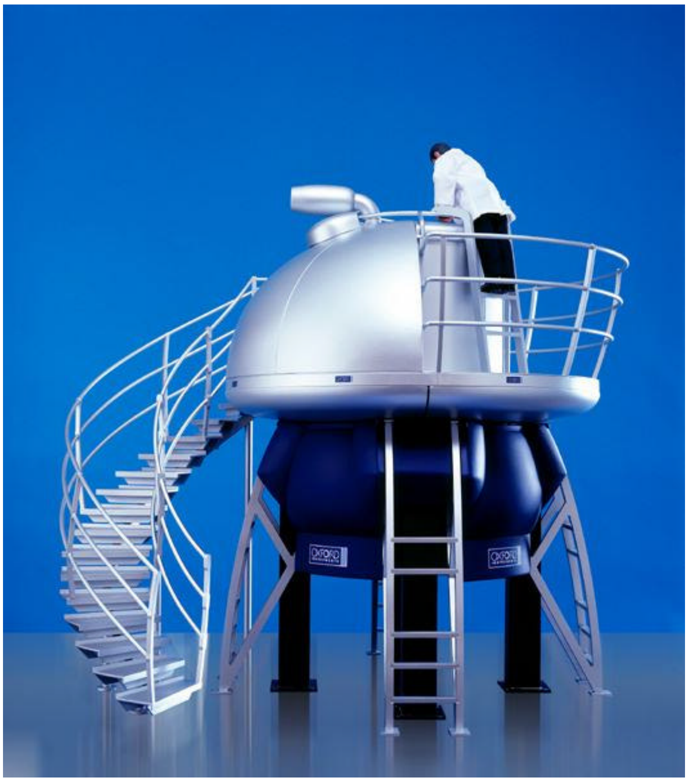

Figure 7: Oxford Instruments 900MGZ 21.1T magnet.

Superconducting Magnetic Energy Storage (SMES) - SMES has found application in power quality by providing protection for short interval power interruption on the order of seconds and as an inductive element in power grid stabilization. American Superconductor both at utilities and end users has installed systems 16 systems (12). These units are usually installed in trailers, which can be quickly sited to respond to power quality problems. Approximately

1/4 tonnes of NbTi superconductor are used in a device. Revenues for FY 2001 were 9.3 million dollars (13). Figure 8 represents a typical D-SMES system currently being sold by GE Industrial Systems through a marketing and sales alliance with American Superconductors.

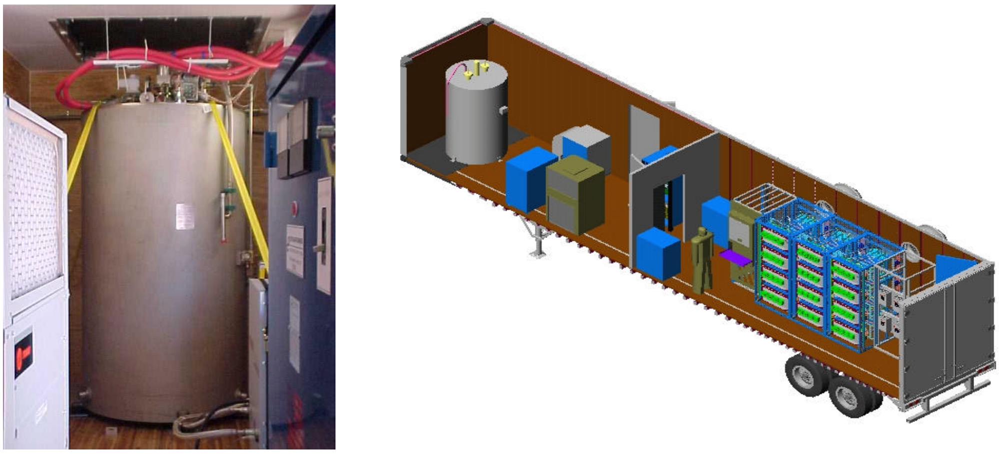

Figure 8: American Superconductors 3MJ/3MW DSMES system in mobile trailer with power conversion modules.

Magnetic Separation - Magnetic Separation is one of the first commercial applications of superconductivity in the industrial arena. The main application is for the removal of iron oxide from kaolin clays to produce whiter higher purity materials used in high quality papers. Oxford Instruments has delivered over 20 systems.

It is estimated that all commercial applications require approximately 150 tonnes of NbTi /year (14). Converting this to contained Nb, adding in the NMR market and assuming a 50% yield as used by H. Stuart in table II results in about 260 tonnes per year of initial Nb metal.

Project Applications

Large-scale projects have played a seminal role in the development and advancement of technology in superconductors. In the early days they were essentially the only markets. High Energy Physics (HEP) requirements for larger and more cost effective accelerators has been the key driver for NbTi development. Similarly Magnetic Fusion has played a like role in development of Nb_3Sn though at a pace somewhat less consistent perhaps due to a smaller political constituency and changes in the politics of energy.

LHC - The Large Hadron Collider being constructed at CERN in Switzerland is by far the largest superconducting project and accelerator undertaken. Projects such as the Tevatron at Fermi, RHIC at Brookhaven and HERA at DESY have paved the way for this ambitious undertaking. Thousands of superconducting magnets will be installed in an existing 27-km circumference tunnel. NbTi is pushed to its practical limits by utilizing the conductor to generate magnet fields of 8.3 T at 1.9K. The conductor will be in the form of a Rutherford cable composed of from 28 to 36 strands of wire as illustrated in figures 2 and 3. Approximately 400 to 420 tonnes of alloy will be purchased over four years for the main magnets and various detectors (14). Figure 9 illustrates the scale of LHC. While Figure 10 show the 2 in 1 magnet configuration that has enabled the costs to be reduced.

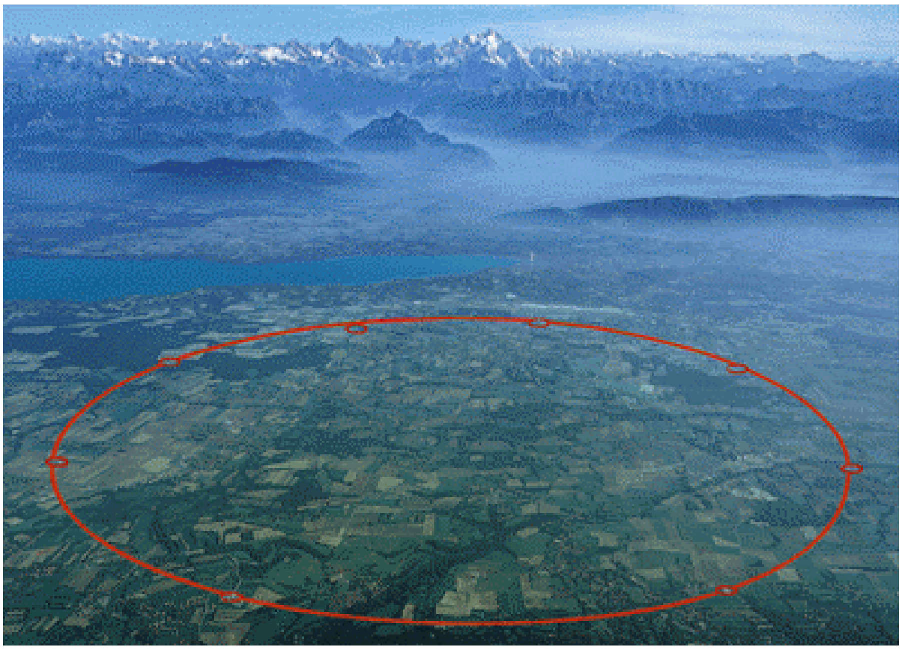

Figure 9: Representation of size of the LHC ring courtesy of CERN.

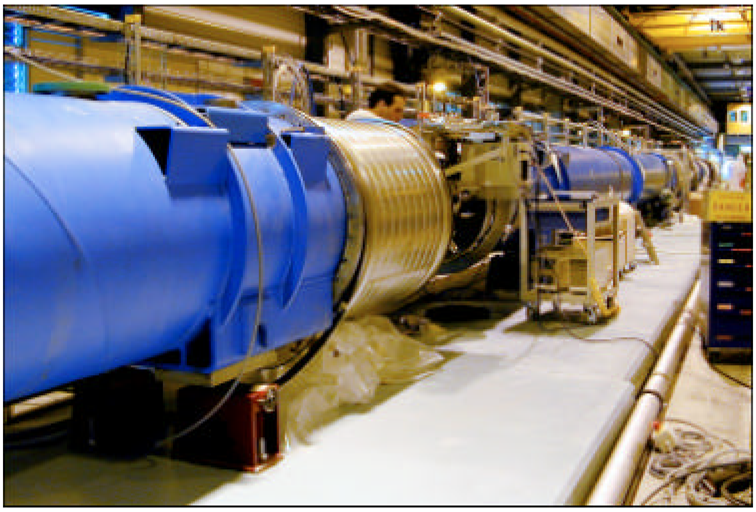

Figure 10: Dipole magnet string for LHC at CERN.

LINAC - Linear Accelerators are used for acceleration of leptons such as electrons, positrons and muons particles. Their light mass precludes circular acceleration, as too much energy would be lost by radiation. High purity niobium is used for the cavities of the superconducting machines such as the Continuous Electron Beam Accelerator Facility (CEBAF) now know as the Thomas Jefferson National Laboratory at Hampton Roads Virginia. The superconductor allows continuous operation of the accelerator. Over 338 niobium cavities are used in the facility to produce a 6 billion electron volt beam. Plans have been made to double the energy.

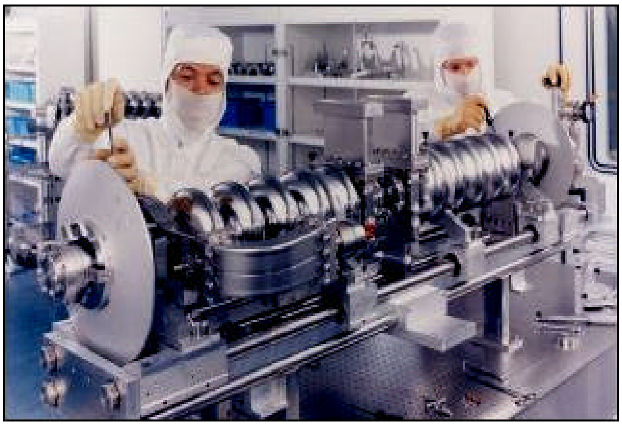

Figure 11: Left -An element of the Niobium RF accelerator cavity. Right - An overview of the Jefferson National Laboratory.

Fusion - The quest for a cheap inexhaustible source of power has continued and is best represented by the international consortium to design and build the International Toroidal Fusion Experimental Reactor (ITER). Because of the high magnetic fields Nb_3Sn is the prime material though if Nb_3Al could be developed at a competitive cost it would find use as well. Currently the project is still in an R&D stage with key device components being developed and tested. Key to the coil construction is development and demonstration of a Nb_3Sn of the Cable In Conduit Configuration (CICC). This has recently been done and tested in a large 13T 150 ton coil at JAERI at Naka in Japan. The Central Solenoid Model Coil (CSMS) is composed of an inner coil built by MIT with the Japanese providing the outer coil and test facility. Approximately 24 tons of Nb_3Sn was used in this coil (15). Figure 12 is a view of the actual inner coil and a cross sectional view of the assembled coil. Unfortunately the US has at this date declined to participate beyond the R&D stage. A reduced cost design is underway which will which may make it more attractive for the U.S to participate. Participation of the US is not a necessity but certainly improves the likelihood of the program going foreword.

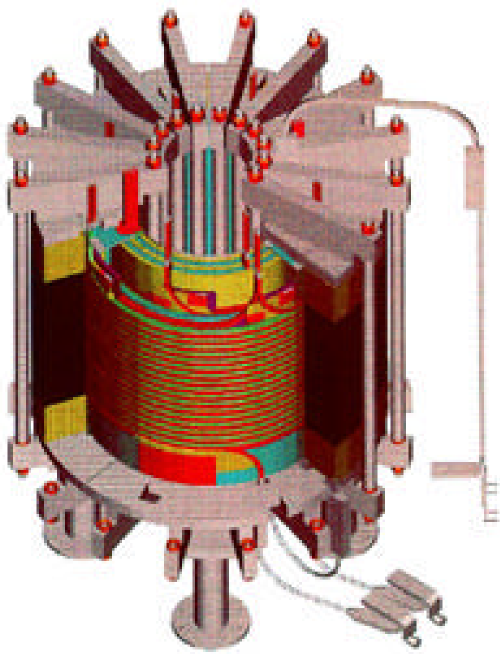

Figure 12: 13T CSMC test coil and cutaway view of assembly.

KSTAR - Korea today is building it's own Toroidal fusion machine employing both Nb_3Sn and NbTi. Approximately *26* tonnes of Nb_3Sn and 12 tonnes of NbTi will be utilized (16). Figure 13 is an overview of the toroidal magnet assembly.

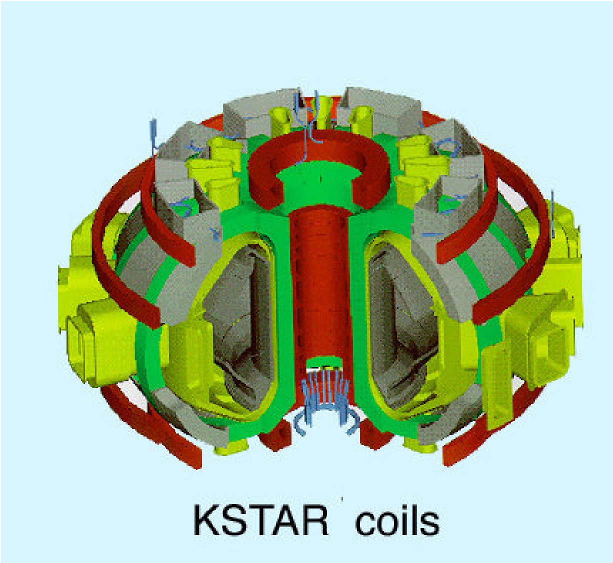

Figure 13: KSTAR Toroidal magnet coil assembly.

45 Tesla Magnet - The National High Magnetic Field Laboratory has recently completed and operated a 2.4 m OD 0.62 m ID CICC Nb_3Sn based magnet to provide a 14 T background field to produce 45 T in a hybrid magnet. Approximately 0.5 tonnes of Nb_3Sn was required (17). Figure 14 is an example of the CICC type conductor used in this magnet and other large Nb_3Sn based projects. Note that to reduce cost copper is cabled in with the superconductor.

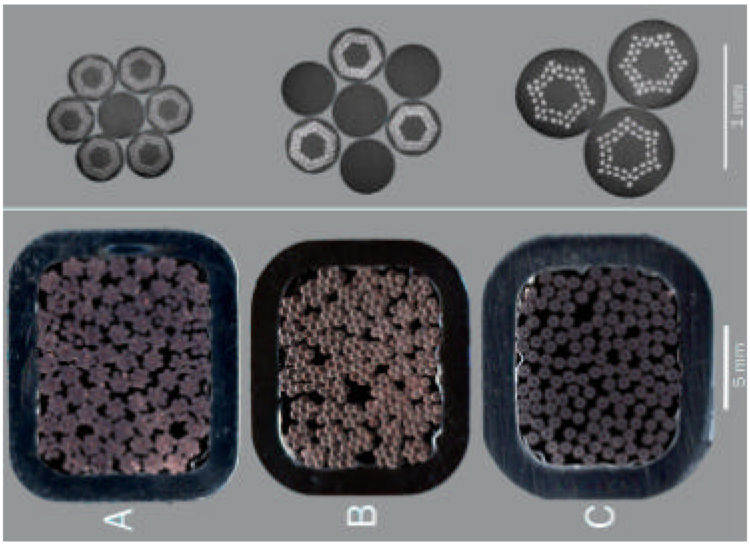

Figure 14: Three conductors used in the NHMFL 45T Hybrid graded magnet

The applications listed are by no means exhaustive, as many projects in Russia, Japan and China have not been covered. It is though representative of the majority of applications.

Current Trends

The present applications certainly provide a basis for projecting trends but would be incomplete without looking at current research both in materials and devices. The next commercial applications could well be influenced if not derived from this research effort.

Materials - Low T_c

NbTi - Large-scale commercialization is continuing to reduce the costs of NbTi conductors. Costs are comfortably below a $1/kilo ampere meter for a typical 5T application. Current density though is only 3% of the theoretical limit (18). Artificial pinning, a concept to engineer in the pinning sites during the construction of the billet has the potential to increase the current density three to five times but work, which began in 1985, has not yet proven practical. The complexity of the process though and present limitations seem to make these conductors only useful for low magnet fields.

Nb_3Sn - The High Energy Physics (HEP) community is now driving the material development for Nb_3Sn and Nb_3Al. Many believe that the next generation accelerator will need the high fields that these materials develop (19). Among the goals for the Very Large Hadron Collider (VLHC) is a cost of less than $1.50/ kAm and a current density at 12 T of 3000 A/mm^2 (20). The author is developing a conductor based on the internal tin process that he believes is a candidate to meet the cost goals with further development (21). The process developed should be scalable to modern NbTi production methods and sizes. Figure 15 is a cross section of the Mono Element Internal Tin (MEIT). The outer layer is copper for stabilization. The next layer is a NbTa alloy diffusion barrier. The filaments are niobium in a matrix of copper and the core is a tin alloyed with titanium to raise the critical field and enhance reaction kinetics.

Nb_3Sn if operated at 5T would have approximately 5 times the current density thereby reducing the cost per $/kAm to below NbTi. Operation at 10 to 12K in a non-liquid helium bath would be a more likely use of a low cost Nb_3Sn then a direct replacement for NbTi at 4.2K.

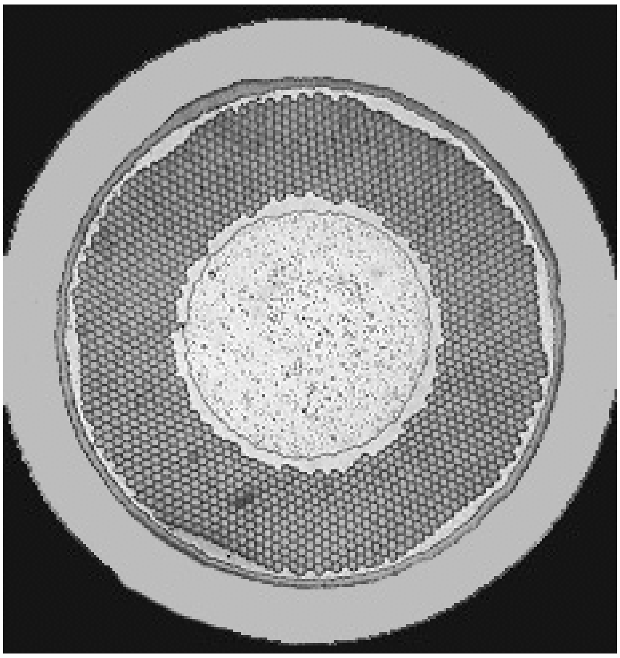

Figure 15: A MEIT process internal tin conductor.

Materials -HTS

High Temperature Superconductors (HTS) - The two main classes of HTS conductors under development are the $Bi_2Sr_2Ca_xCu_xO_x$ (BISCCO) and $Yba_2Cu_3O_7$ (YBCO - 93K). BSCCO-2212 (90K) and BISCCO - 2223 (107K) conductors require a silver matrix and have relatively low current densities. Materials such as $HgBa_2Ca_2Cu_3O_x$ with a critical temperature of 134K could offer future promise but like various A15's may never prove practical. The BSCCO conductors are considered transitional in that they provide material for prototype devices but are unlikely to be widely adopted because of their high cost. Figure 16 is a process outline for BSCCO-2223 and is similar in fabrication technology to conventional LTS. Figure 17 is a typical BSCCO -2223 conductor.

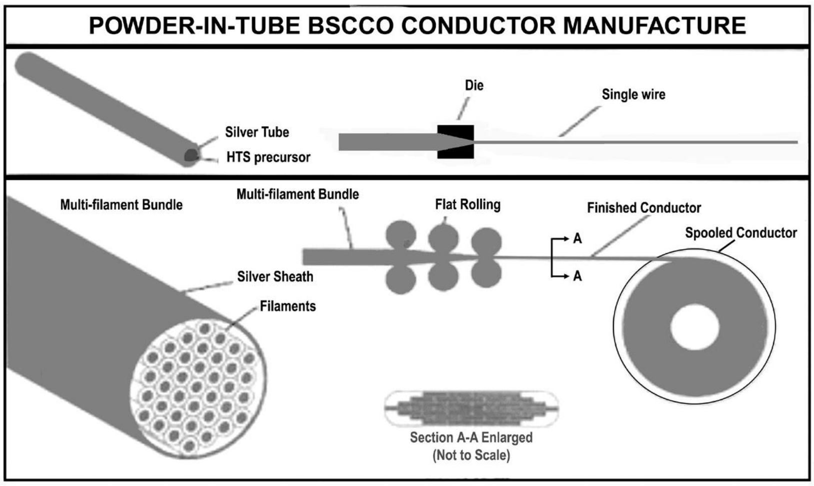

Figure 16: IGC-SuperPower LLC process outline for BSCCO 2223 HTS conductor.

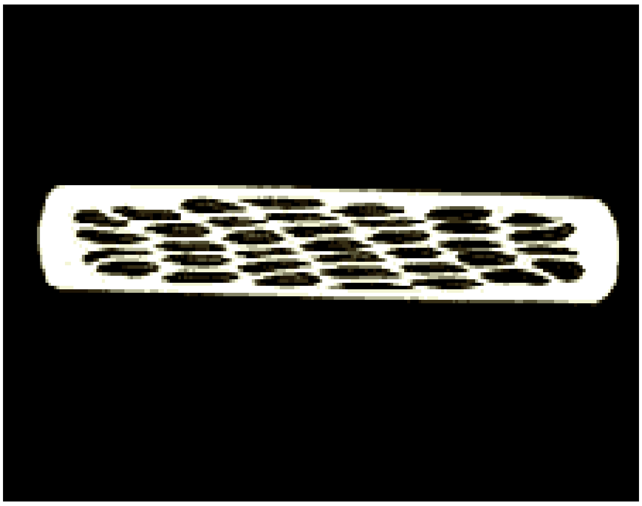

Figure 17: IGC-SuperPower BSCCO conductor.

YBCO on the other hand holds the potential to be able to deliver comparable performance to NbTi and Nb_3Sn at significantly higher temperatures. Two competing processes are under development in conjunction with industry, the Ion Beam Assisted Deposition (IABAD) pioneered by Los Alamos National Laboratory (LASL) in 1995 and Rolling Assisted Biaxially Textured Substrates (RABiTs) pioneered by Oak Ridge National Laboratory (ORNL) in 1986 (22). Both are aimed at assuring the layer of YBCO is deposited in an oriented and aligned epitaxial manner. Figure 18 is a new pilot tape deposition facility at IGC-SuperPower LLC.

Figure 18: A YBCO pilot facility at IGC-SuperPower LLC.

Device and Application Trends

MRI - MRI is incorporating higher magnet fields for functional imaging, image guided surgery and more patient friendly open systems. MRI's range of application continues to increase. A typical 3 Tesla magnet uses four times the NbTi than a 1.5 T. Open systems are magnetically inefficient and hence use substantially more material than a closed system of the same size (8, 23). Open systems are cryogenically more complicated so that the use of conduction or gaseous cooling would be more advantageous. Figure 19 is a GE MRT Nb_3Sn magnet introduced several years ago operated at 10K and used during an operation for real time image guided surgery. The system is perhaps ahead of its time but certainly shows a direction both for materials and application. Another 1T open system just introduced by IGC is shown in figure 20.

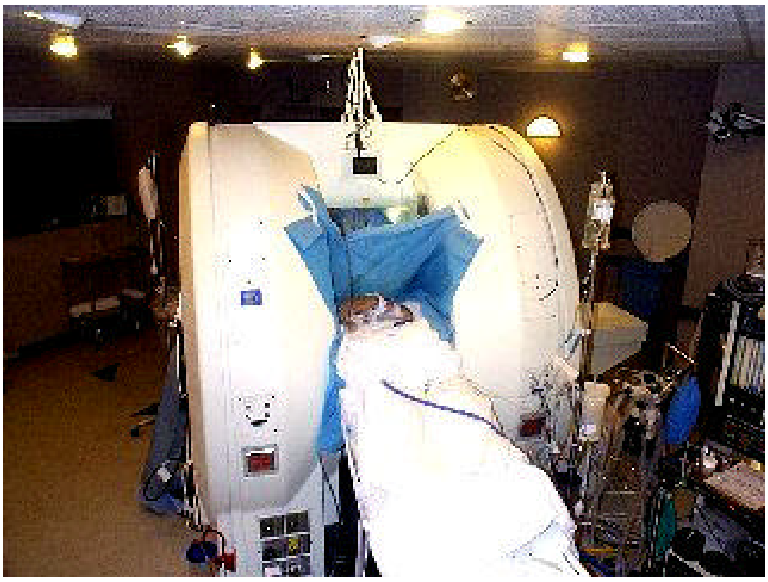

Figure 19: GE Medical Systems MRT Nb_3Sn MRI system for use in the operating suite.

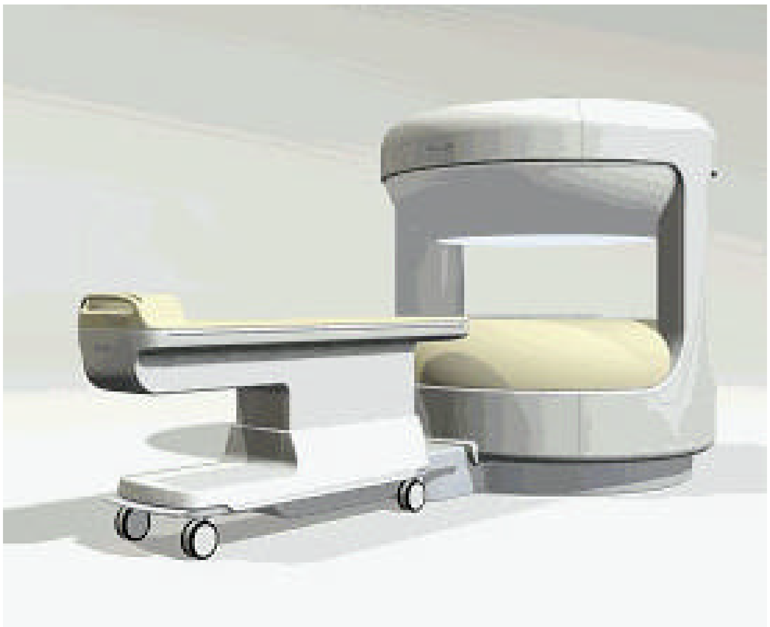

Figure 20: A Phillips Medical System 1T open system with and IGC MRI magnet.

Work is currently proceeding on developing magnets for Hall Effect Imaging for detection of cancer (24). Surgery using superconducting magnets to guide magnetic catheters is another interesting area of development (24). Certainly the use of superconducting magnets in imaging, medical analysis, chemical and biochemical analysis is a growing with new procedures methods and techniques being developed continuously.

Project Applications

HEP - The Gilman report has laid out a path for future HEP research (25). The choice of machine is still far from settled but much work is already being done on developing conductors for the VLHC. A rough estimate for the high field version might need 150,000 tonnes of Nb_3Sn conductor representing about 5000 tonne of Nb. A 20-year time frame for completion with 10 years of development is likely (19).

Fusion in some version of ITER also presents a significant opportunity though also on a similar time frame. Quantities are uncertain at this time but substantial (200 to 500 tonne).

Cryogenic Refrigeration

Attempting to project the future of Nb in superconductivity without considering cryogenic refrigeration would leave out an important but often overlooked component of the economic and reliability component of the commercialization of superconductivity. The success of MRI is very much related to the reliability of the cryogenic system. Magnets today have shield coolers that allow continuos operation of the magnet with a greater than two year interval for addition of liquid helium. Some units are equipped with re-condensers that completely remove the need to add liquid helium (8). Pulsed tube technology is being introduced to further improve the reliability by eliminating the moving parts in the cold head of the refrigerator (26).

To get a rough understanding of the energy costs between HTS and LTS conductors it is useful to consider the power requirements of a typical commercial device such as a MRI machine using LTS versus HTS. A typical MRI shield cooler requires 3.7 kW to deliver 40 W at 45K to the outer shield and 0.6 kW to delivere1 W at 11K to the inner shield (27). For an HTS MRI to deliver the same 40 W at 77K with a typical Carnot efficiency of 10% would require about 1.2 kW. Hence the cryogenic power ratio between LTS and HTS would be about 3.6/1. It would cost about $140/day more to operate a LTS device based on $0.08/kWhr electric cost than a HTS device. Capital cost for a small system for HTS is about $155/W or about $6000 while a two stage Gifford McMahon refrigerator for LTS operation costs about the $10000 (28). The DOE has set a goal for HTS refrigeration of Carnot efficiency greater than 30% and a capital cost of about $25/W (28). This goal along with conductor performance cost is considered necessary if HTS is to find wide scale application in the power sector. Bulk liquid nitrogen if accepted for HTS power applications is inexpensive enough to meet the cooling cost goals.

1981/2001/2011- A Comparison and Projection

Projected Impact of HTS

DOE has defined price and performance targets for HTS superconductors and for the required refrigeration for the technology to have an impact in the power sector. Power applications include fault current limiter, motors of 1000 HP or greater, generators of 100 MVA or greater, transmission cables, and transformers (22). Most require costs of less than $10/ kAm to be economically viable with the required refrigeration efficiency and cost as discussed in the previous section. Figure 21 illustrates the costs of both HTS and LTS as of 2000 for the various materials (8). The $10/kAm line is the goal for HTS. Applications such as transmission lines, transformers and fault current limiters do not require the HTS conductors to operate in a significant magnetic field. Bismuth based conductors at 77K have significant declines in current density with field making them more suitable for low field applications (22). Higher fields rapidly shift the cost line towards the $100/kAm and above. American Superconductor believes its new plant can produce BISCCO at about $50/kAm a cost considered acceptable for some underground transmission applications. Current price quoted by American Superconductor is $200/kAm at self-field (29). YBCO is much less field dependent and has delivered well in excess of 3 mega Amperes at self-field (30).

Irrespective of cost HTS conductors have some significant inherent drawbacks that limit their range of application. HTS conductors exhibit a phenomenon known as flux flow, which limits their use as replacement for LTS conductors in magnets operated in the persistent mode such as MRI. Also YBCO inherent geometry makes it very difficult to filamentize the structure thereby increasing the losses in AC power applications. Higher operating temperatures will tend to mitigate the refrigeration penalty.

The manufacturing and technical challenges to produce a cost-effective conductor by an area rate process versus a volume rate process, as in LTS conductors are significant. Spending for development by the DOE in its SPI programs cost matching and capital raised by the public is probably in excess of $80 million per year. Japan has a national effort funded at greater than $105 million/yr. (31).

Various studies assume anywhere from a five to ten year time frame for HTS penetration in the power segment (32). Ten years is assumed to be realistic considering the difficulties of the technology and market acceptance. First applications are likely to be in power transmission which requires the least in conductor performance but the most in cryogenic performance Power transmission could be the first commercial use of HTS conductor that meets the cost targets. A demonstration line of 3 30 m cables is delivering power to three Southwire plants as of Feb 16, 2000 (33).

Looking foreword ten years it appears that HTS will meet the requirements of the power sector in some of the applications originally envisioned for LTS conductors. Existing applications for LTS are not likely to be challenged seriously by HTS for several reasons. The first reason is that the market opportunity for HTS material and engineering development required is much more lucrative than penetrating the LTS market. The second is that HTS materials have significant drawbacks as discussed as a direct replacement for LTS and finally the cost and performance of LTS devices will continue to improve making replacement even less attractive.

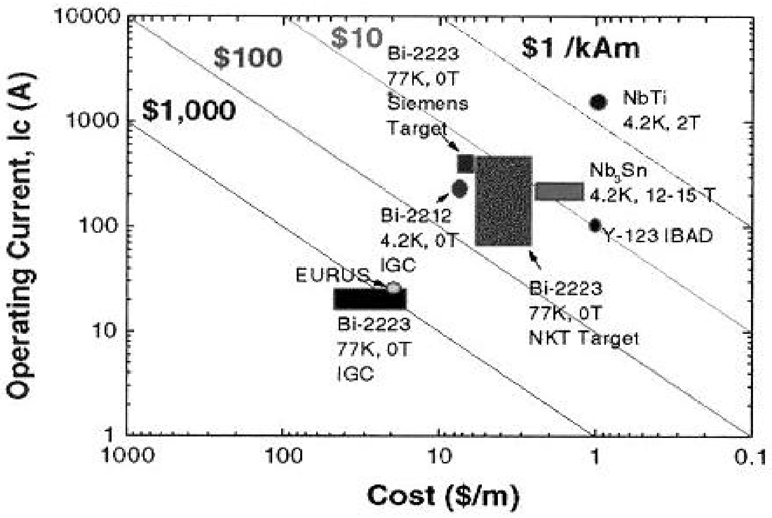

Figure 21: Performance cost ($/kAm) for various materials (8).

Comparison with Prior Forecast and Projection for 2011

The projections presented forecast only to 2011 as beyond that period HTS and other factors such as technology changes and market saturation are likely to have an impact on the market for niobium based superconductors. That is not to say that Nb based superconductors in 2021 might be larger or as larger as in 2011. B_2Mg is unlikely to have much of affect except in niche markets as it's likely operating temperature is too low for power applications and not high enough to impact the market for LTS conductors in the time frame considered.

Table III Comparison of 1981 Nb usage for 2000 and a projection for 2011 Tonnes of Nb

Application	2000 HS Projection	2000 estimate	2011projection
MRI/NMR/Lab Magnets	175	173	290
FTIR	0	9	15
HEP	80	58	50-600
Fusion	230	5	10-100
SMES	16	3	40
Magnetic Separation	2	1	2
MHD, LevitatedTrains, Generators, Power, Ship Propulsion, Gyrotrons,	185	1-5	1-10
Total	688	250-255	408-1057
Total Nb required at 50% yield	1376	500-510	816-2114

MRI/NMR/Lab Magnets - It is remarkable how close H. Stuart's projections for these applications are to the present estimate. The estimate for the future takes into account greater application MRI/NMR and a shifting to higher field more material intensive applications.

Open magnets, which will become a greater percentage of MRI systems may shift to Nb_3Sn for cryogenic design flexibility and low to no liquid helium based systems.

FTIR represents a class of new instruments, which could grow at a greater rate than projected.

HEP - The 2000 projection is not far from the actual. If SSC had been built the projection would have been significantly under. HEP in the future represents an enormous potential though the when and the type of device are uncertain. The upper number represents high field VLHC machine with conductor purchased over eight years beginning in 2011. The lower number is an educated guess of what a low field system using iron might require.

Fusion - The 2000 projection was far from the mark reflecting the continuing uncertainties of magnetic fusion as an answer to the energy situation. Certainly in 1981 fusion looked like a key solution to the energy situation. It appears we are once again looking at a similar situation though there is no evidence that fusion will see increased emphasis and funding. The 2011 projection is an assumption that some magnetic based machine will be built though at a size and time frame still quite uncertain.

SMES - SMES for power quality and grid stabilization has a potential world market of $ 2 billion (34). It is assumed that approximately 5% of the market will be penetrated by 2011.

Magnetic Separation is assumed to proceed at its current slow pace. HTS may penetrate and grow this market, as liquid nitrogen temperature operation is more attractive for mines often at remote locations.

MHD, Levitated Trains, Generators, Power, Ship Propulsion, Gyrotrons, - Only Levitated trains are still be pursued with LTS materials. The other applications have not been adopted either because of lack of economic feasibility or through changes in government priorities. HTS though promises an economic solution in the future for many of the power sector and propulsion applications.

Conclusion

Niobium utilization for superconductivity has grown at less than half the forecasted rate of the projections in 1981. The cost effectiveness of many of the projected applications has not been amenable to low temperature superconductors. In addition, false hopes and starts by government sponsored programs influenced expectations. Still niobium as a superconductor has significant practical and projected applications that indicate that the projections of 1981 for 2000 may only have to wait another ten years. HTS superconductors are not expected to penetrate significantly current LTS markets but will better serve power sector markets, which 20 years ago were, part of the hopes for LTS.

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