RESEARCH AND DEVELOPMENT ROADMAP

(Final Draft)

Achieving Advanced Electrical Wires From Superconducting Coatings

Research and Development Roadmap
to
Achieve Electrical Wire Advancements
from
Superconducting Coatings

(Final Draft)
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EXECUTIVE SUMMARY

The U.S. Department of Energy (DOE) leads the national effort to bring the advantages of High Temperature Superconductivity (HTS) to the way electricity is generated, delivered and used. The Office of Utility Technologies Superconductivity Program for Electric Systems conducts multi-disciplinary, cost-shared research to obtain high currents in electrical wires made of HTS materials and to design high efficiency electrical devices using these wires. The strategic plan is contained in *Superconductivity for Electric Systems Program Plan (FY 1996 - FY 2000)*. Device design activities have been supported since FY 1993, when wire manufacturers were first able to provide long (over 100 meter) lengths of superconducting wire made of the ceramic HTS compounds. Over 150 kilometers were supplied last year to program participants designing motors, generators, power cables, current controllers and other devices.

Meanwhile, exciting program discoveries were made at Los Alamos National Lab in FY 1995 and at Oak Ridge National Lab in FY 1996 for a second generation HTS wire that meets performance and cost goals for commercial versions of the devices now being designed. The first generation wire is made by packing a silver tube with HTS powders and then following a series of thermal and mechanical processing steps to obtain long lengths with the ability to carry electric current. The new, second generation wire, method is to prepare metal strips so that HTS coatings deposited on the strips will be highly aligned and able to carry very high currents.

Interest in advancing this new technique is intense; in this country as well as in Europe and Japan. Several research consortia are already working with the national labs, each with a potentially promising coating method.

This roadmap has been prepared to guide and accelerate this research by laying out the individual steps that experts believe need to be taken in order that coated conductors fulfill their promise. The University of Tennessee Space Institute has led this roadmapping effort which has been carried out by a team of experts from private companies, the national labs, and universities. The intent is that by knowing the entirety of what needs to be accomplished, work on these various tasks can proceed in parallel and reduce the overall development time to the window in 3 - 5 years set by companies intending to begin commercial development of a broad range of commercial products using HTS wire in the time period 2000 - 2010.

Background

Superconductivity describes the ability of certain materials to carry, or conduct, large amounts of electric current without resistance energy losses. This mysterious state of grace was originally, and unexpectedly, discovered in 1911 when a research lab in the Netherlands gained the ability to reach temperatures near the absolute zero possible (-459.67 Fahrenheit). The electrical resistance of a sample of mercury was found to vanish when it was cooled to these very low temperatures. Excitement swept the world over the possibility of transmitting electricity with near-perfect efficiency and building better electrical equipment of all kinds. A Nobel prize in physics was awarded. This experience was repeated in the late 1980's by the discovery of high temperature

superconductivity; a new class of ceramic materials that lose electrical resistance when cooled to the relatively balmy temperatures of atmospheric liquid nitrogen (- 321 Fahrenheit). The news made front page headlines all over the world because of the possibility of using electricity with near-perfect efficiency and a Nobel prize in physics was awarded in 1987 for HTS.

Prior to the recent discoveries, widespread use of superconductivity in electric applications was impractical. The problem was first the inability to make usable electric wires during the period 1911 to the 1960's, and then the problem became the unacceptable costs of refrigerating wires to the near absolute zero temperatures required. HTS seemed to be the answer to the latter, until 1990 when the difficulty of making flexible, high current wires from the HTS ceramic material seemed intractable - even to the hundreds of highly talented PhDs working on the problem all over the world.

Fortunately, in 1991 a group at Vacuumschmelze in Germany found that the Powder-in-Tube or PIT method described above made possible long wires using one of the HTS materials, bismuth-strontium-calcium-copper oxide. Companies in the US and Japan quickly duplicated these results and long lengths of wires with quite good performance became available to engineers wanting to design devices by 1993. Two difficulties remain with the bismuth wires; they need to be cooled far below liquid nitrogen temperature to be used in devices needing magnetic coils, such as motors or generators. Second, the predicted cost for manufacturing wires (now near $3 per ampere-meter) by this method appear to be a barrier to their wide-spread use in a broad range of applications where a cost near $0.01 per ampere-meter is desired.

Objectives

Second generation wire processing can potentially make use of any of the several known HTS compounds, while PIT was only found to work with the bismuth compounds. The present leading candidate material, yttrium-barium-copper oxide, has the advantage of being able to carry high currents in strong magnetic fields while being cooled by liquid nitrogen. This advantage is shared by other rare earth substitutes such as neodymium as well as by thallium compounds. Cost projections for eventual long length manufacturing are presently close to that desired for widespread application.

The problems associated with wire development can best be understood by considering the most critical performance measure - current density. Current density is simply the amount of current, expressed in amperes, flowing through a cross-section of wire, expressed in square millimeters. For comparison copper or aluminum wires are usually operated between 2 and 5 amperes per square millimeter in order to avoid overheating the wire and to avoid incurring large resistance energy losses. HTS wires, in a direct comparison, will operate at 500 amperes per square millimeter with no resistance energy loss. Presently, the superconducting coating of coated conductors has a current density of 10,000 amperes per square millimeter in short lengths. However, when the thickness of the metal strip is considered (as it must be), the current density is 100 amperes per square millimeter - still far better than copper, but below the ultimate potential. The challenges to development of coated conductors are:

- minimizing the thickness of the metal strip while still providing mechanical strength and providing a template for aligning the superconducting coating.

- developing a scalable coating process that provides 10,000 amperes per square millimeter in the coating in short lengths and can potentially provide long wire lengths at or near $0.01 per ampere-meter.

- developing a coating process that provides 10,000 amperes per square millimeter in coatings thicker than 1 μm (perhaps 5) to increase both current density and current.

- developing an encapsulation method that provides the needed mechanical strength and chemical stability while still attaining operating current densities of 500 amperes per square millimeter or better in kilometer lengths of wire.

    This document details a roadmap for preparing the metal strip (including substrates and buffer layers), coating processes, encapsulation (including passivation) and process development based on technical requirements for each performance characteristic of the final wire form.

Technical Roadmap for the Development of Practical Superconducting Coatings

Single Crystal Substrate

Textured Substrate 1 cm.

$J_c > 5,000 \ A/mm^2$

$J_c > 1,000 \ A/mm^2$

Sharpen Texture

Buffer Layers

Final HTS Coating

Industrial HTS Wire Requirements

Longer - Continuous 1 m.

Feasibility Determination

Pilot Facility 10 m.

Pre-Commercial Facility 1000 m

ISSUES:

Geometry
J_e, J_c

Architecture Thickness Scale-up

Rate of Growth Quality Surface Roughness
J_e, J_c
Capital Requirements Cost

Demonstration Scale-up Equipment Process Control Operating Window Material Supply Quality Control
J_e
Cost Non-Integrated Facility

Cost Uniformity
J_e

ACKNOWLEDGMENTS

1. Introduction

1.1 Program Definition:

The U.S. Department of Energy (DOE) conducts research in high-temperature superconductivity (HTS), as one of the programs of the Office of Utility Technologies. That program focuses on power applications of HTS which are of interest to electrical utilities and industrial equipment suppliers. In addition to research conducted at various national laboratories, DOE has assigned the University of Tennessee Space Institute (UTSI) the task of developing a roadmap indicating how to get from the research laboratory to commercial production of second-generation HTS wire. UTSI conducts their work under the auspices of the Federal Energy Technology Center (FETC) in Pittsburgh.

Figure 1.1 is excerpted from *Superconductivity for Electric Systems Program Plan (FY 1996 - FY 2000)*, which is the plan for the DOE Superconductivity Systems Program [1]. This figure is a portion of Figure 3 of that report. Here we are concerned with one specific subset of the overall superconductivity program: making wire capable of carrying over 100 A/mm^2 (J_e) in magnetic fields of 5 tesla (T) at liquid nitrogen temperatures. No such wire exists yet, and it is the purpose of the second-generation wire program to develop it. Specifically, the goals of the program envision commercially successful wire that is made entirely by the private sector. (Low-temperature superconducting wire made of NbTi enjoys exactly that position today.)

In the following sections, we strive to lay out a roadmap by defining a large set of "issues" deserving attention, and clustering these issues into categories of obstacles to be dealt with. The issues are tabulated in Table 1.1, and are discussed in sections 2 and 3 below. The primary milestones are collected in section 4. It must be recognized that competing technology does not stand still, and this is covered in section 5. The explicitly technical priorities of the program are stated in section 6. Section 7 is a summary; ancillary supporting information appears in the appendices.

1.2 History

The foremost characteristic of a good roadmap is to avoid "detours" and "washed out bridges". Accordingly, it is necessary to look over the horizon and anticipate what difficulties will likely be encountered along the way. The history of HTS research leading to first-generation wire provides background and offers guidance for the future [2].

In 1986 two IBM scientists, Georg Bednorz and Alex Müller [3], announced the discovery of a material that was superconducting at 34 K, 11 degrees warmer than had ever before been observed. Within a year, scientists in the U.S. and Japan created new compounds with yet higher superconducting transition temperatures. In fact, by March 1987 eight new materials were produced that are superconducting above 77 K, the boiling point of liquid nitrogen at standard atmospheric pressure. (Liquid nitrogen is an efficient cryogen, inexpensive, easy to insulate, inexhaustible, readily available, and non-polluting.) One of these, $YBa_2Cu_3O_x$ (YBCO), has all the

desired characteristics for use in the electronics industry but lacks one feature essential for use in power applications: ability to be formed into wires by thermo-mechanical means.

In the late 1980's, scientists turned their attention to the Bi(Pb)SrCaCuO superconductor, a family of HTS that has plate-like grains that align easily when wire-forming processes are used. This family of wires is produced by what is commonly referred to as the oxide powder-in-tube (OPIT or PIT) process. For this, a silver or silver alloy tube is loaded with precursor powder. The tube is then sealed and drawn into a fine wire. These round wires are cut and re-stacked into another hollow tube and, after a series of additional drawing, rolling, and heat treatment steps, multi-filamentary ribbons (or "tapes") are produced with the desired superconducting phase assemblage and texture. Lengths of BSCCO wire as long as 1 km are now routinely produced by companies in the U.S. and Japan. At liquid nitrogen temperatures, these wires can have overall engineering current densities in excess of 100 A/mm^2 with no applied magnetic field. This performance degrades by an order of magnitude at 77 K upon application of just a few tenths of a tesla magnetic field. Thus, in order to use these wires in electric machinery, such as motors, generators, transformers, and energy storage magnets, the wires must be cooled to temperatures in the neighborhood of 20-30 K using helium gas or a closed-cycle cryocooler. Since superconducting, rotating electric machines may need fields as high as 5 tesla, and since today's magnetic resonance imaging machines typically generate fields of 1 to 4 tesla, new wires are needed that can take advantage of the simpler, less-costly cryogenics requirements associated with operation at liquid nitrogen temperatures (65-77 K).

The YBCO compound has the unfortunate problem that its grains are difficult to align. In HTS, electric current doesn't flow well from grain to grain through high-angle grain boundaries. Coatings on silver and silver alloys have also proven to make poor superconductors, due to low superconductor densities and poor grain alignment. So, while YBCO is useful for making thin films on single-crystal substrates for electronics applications or for small discs for bearings, something else is needed for wires.

In 1988 Lawrence Berkeley National Laboratory [4] initiated work to form YBCO tape conductors by depositing films on metal substrates. This was a modest effort, and was regarded as risky since it seemed likely at the time that a way would be found to make more conventional wires of the YBCO compound. However the weak link problem, caused by incomplete alignment of film crystallites, proved highly intractable. It thwarted the conventional approaches, and nearly prevented success with deposited film conductors as well. Fortunately, YBCO film growth itself was not a problem; there were literally hundreds of papers reporting the successful growth of high-current films by epitaxial film growth on single-crystal substrates. Single-crystal substrates are useful for electronic applications. However, for electrical applications (that is, long wires) strong temperature-resistant nickel-alloy substrates coated with yttria stabilized zirconia (YSZ) buffer layers took the place of the single-crystal substrates. The films of YBCO and YSZ were deposited with the pulsed laser deposition (PLD) technique. The YBCO crystallites readily formed with the correct c-axis orientation normal to the substrate, but the in-plane orientation was random. As a result the critical current density of YBCO films on metal [5] and polycrystalline YSZ substrates investigated by Oak Ridge [6] appeared to be limited to about 100 A/mm^2 (77 K, 0 T). Thus, in-plane orientation appeared to be necessary.

Ion beam assisted deposition (IBAD), as applied by Lawrence Berkeley National Laboratory [7], and an independent group at Fujikura in Japan, proved to be a solution to the texturing problem. This increasingly popular technique utilizes the bombardment of a growing film with energetic

ions, resulting in improved texture. While a normally incident beam is usually used (but see [8]), the Berkeley group found that an oblique ion beam can introduce the needed in-plane orientation in the YSZ buffer layer. Epitaxial growth of the superconducting YBCO film then resulted in critical current densities up to 6,000 A/mm^2 [7], an enormous improvement.

Two new processes have been under development since 1991 that promise a new way to manufacture flexible, high current density wires made from YBCO, something that has eluded researchers since the discovery of YBCO in 1987. These wires offer impressive performance opportunities at liquid nitrogen temperatures. In both cases, the key is to prepare a textured substrate, or "template," on which the YBCO may be deposited as a thick film. Done correctly, the YBCO grains are well-aligned, mimicking the alignment of the underlying substrate, resulting in the prospect of long-length wires that are strongly-linked. Biaxially-textured substrates, where the atomic planes of the grains in each layer of the substrate are well-aligned in the surface of the tape, represent one potential solution to the shortcomings to fabrication of long-length YBCO wires.

The national laboratories attacked the YBCO weak-link problem in two different ways. The Los Alamos group worked to improve the IBAD process, refining the quality of the angular alignment of the YSZ crystallites, and introducing an additional cerium oxide buffer layer which eliminates the tendency of a few YBCO grains to crystallize with a 45 degree misalignment angle. The Los Alamos process is illustrated in Fig. 1.2. With this process current densities reached 8,000 A/mm^2 in 1994 [9] and 13,000 A/mm^2 in 1995 [10].

Oak Ridge National Laboratory researchers turned their attention to developing sharp biaxial textures in metals, such as nickel and copper, and then depositing on them additional, chemically-benign metal layers with epitaxial orientation similar to that of the underlying metal strip. In the most recent architecture, Oak Ridge deposits the oxide buffer layers directly on the nickel tape, with no intervening metal coating on the nickel. Like Los Alamos, the thin oxide buffer layers are placed on top in order to transfer the alignment to the superconducting layer while avoiding chemical degradation, but Oak Ridge relies on the alignment of the first metal strip instead of the IBAD process to provide the template for the superconductor (see Figure 1.3). Oak Ridge calls its substrate technology "RABiTS™," or rolling-assisted, biaxially-textured substrates [11,12,13].

The Oak Ridge group produced the simplest version of their substrate using a dual metal oxide buffer layer architecture and a common industrial film growth technique, called electron beam evaporation. For this, extremely thin layers of two ceramic materials are rapidly deposited sequentially using a laboratory-scale electron beam system. A cerium oxide layer as thin as 100 angstroms is placed "almost instantaneously" on the rolled nickel, followed by a 140 nm layer of yttria-stabilized zirconia. In the lab environment, this layer takes about 20 minutes to grow. The ceramic layers in the RABiTS sandwich are, therefore, remarkably thin.

1.3 Second-Generation Wire

The "first generation" of HTS wire is made from BSCCO [14], and several companies have succeeded in making long (> 1 km) lengths [15,16]. However, it is still quite delicate and very expensive, and cannot stand alone as the commercial product for all HTS applications. Applications using such wire are under development by various companies engaged in CRADAs with national laboratories, so there is still a substantial government subsidy.

BSCCO is by no means an ideal material, since it carries little current when used at 77 K in high magnetic fields. BSCCO needs to be refrigerated to near 20 - 30 K to carry high currents in

high magnetic fields. Therefore, researchers have continued to search for other forms of wire using HTS materials such as YBCO and Thallium-Barium-Calcium-Copper-Oxide (TBCCO). Such efforts using the OPIT approach have, to date, been disappointing because these compounds do not readily form wire like BSCCO.

As described earlier, the key to attaining high current capacity in YBCO is to achieve good grain alignment, which begins with alignment of the substrate material [17,18,19]. For preparing the substrates, the two leading candidate technologies are known as IBAD (Ion Beam Assisted Deposition) [7,9] and RABiTS (Rolling Assisted Bi-axially Textured Substrates) [11,12]. The question at hand is: can either of these methods lead to a manufacturing technology for long lengths of *wire* that will ultimately be a profitable product?

High critical current densities have been achieved using the RABiTS and IBAD substrates. The magnetic field dependence of the critical current density is shown in Figure 1.4 for the RABiTS and IBAD samples recently produced by the laboratories. LANL has produced short samples with absolute critical currents of 200 amperes (75K, self-field) and critical current densities in excess of 10,000 A/mm^2. The sample was 1 cm wide and 4 cm long. ORNL's RABiTS sample (3 mm x 15 mm) produced a critical current of over 30 amperes (77 K, self field) and a critical current density of over 7,000 A/mm^2; a 1 mm wide bridge was used for the self-field measurement. At 75 K (the boiling point of liquid nitrogen at Los Alamos), the Oak Ridge samples yield J_c's of >10,000 A/mm^2.

The Superconductivity Technology Center at Los Alamos National Laboratory has been developing continuous coating processes for both the IBAD textured layer, and for buffer layers and YBCO by pulsed laser deposition. The current IBAD system has been routinely producing 20 cm long stationary tapes using a 20 cm linear ion assist gun, and modified to deposit the textured YSZ layer on a continuous loop of tape 113 cm long. The YBCO coating must be applied at elevated temperatures, so a system was developed to transport the 113 cm loop over a heated roller. The laser generated vapor plume is then directed at the heated portion of the tape.

Using these systems, a number of 20 cm by 1 cm superconducting tapes have been fabricated. The best results to date (75K, self-field) are an I_c of 70A over a measurement length of 12 cm (the measurement length is less than the original tape due to the splices used to complete the loop, and the current lead attachments). For this tape the YBCO thickness was 1.7 microns, so the average J_c was over 4,000 A/mm^2. To investigate uniformity, the tape was cut into 1 cm lengths and patterned into 500 µm by 5 mm bridges. The highest bridge J_c was 8,000 A/mm^2. On a separate tape with a thicker YBCO film, an I_c of 96A was measured over a 1 cm length: considering the 0.004 inch thickness of the sample, the engineering current density was nearly 100 A/mm^2. The next step is to produce full 113 cm lengths, which will begin as soon as the IBAD system modifications are completed.

The LANL samples have bend strain tolerance. The sample will sustain a maximum tensile strain of 0.5% and can be bent around a 2.5 centimeter mandrel with no current degradation. At 1 tesla, critical current densities of 1,500 - 3000 A/mm^2 (77K) have been measured across the full sample width at both laboratories.

The sample wires produced to date, while short (a few centimeters in length), have generated tremendous interest among those who would use these wires in applications requiring strong magnetic fields. The coated conductors operating in the liquid nitrogen regime outperform the metallic superconductors (NbTi, Nb$_3$Sn) at 4.2 K. Moreover, even in the worst field direction (H || c) and for temperatures below 65 K, the short-sample YBCO coated conductors operated in an

eight tesla background field have at least a factor of three higher critical current density than pre-commercial BSCCO-2223 wires with *no applied field* (Figure 1.5).

Tapes coated with YBCO thick films offer many advantages over alternative superconducting wire technologies. The ability of these coated tapes to carry large electric currents with low resistive losses when cooled with liquid nitrogen is a major benefit. Another distinct advantage of coated conductors is the combination of the high current density, J_c (77K), of over 10,000 amps/mm^2 with the absolute current of 200 amperes observed in a 2 mm thick film that is one centimeter wide. Possible deposition of such films on both sides of thin tapes (1-2 mils thick) offers the opportunity to achieve very high engineering current densities. One of the most exciting opportunities these new conductors may offer is the prospect of a single layer transmission cable with fewer tapes than are required with the OPIT materials and with greatly reduced AC losses. In addition, the excellent behavior of the YBCO-based tapes at liquid nitrogen temperature and subjected to high magnetic fields directed along the tape plane is also a distinct advantage over alternative HTS materials.

In addition to cables, there are many potential applications for YBCO coated tapes. Due to their ability to support high currents in magnetic fields above 2 tesla, several HTS applications (such as motors, generators, transformers, current limiters, and magnetic energy storage) may eventually be commercially feasible due to the ability to operate at liquid nitrogen temperatures (65-77K). Magnetic separators based on HTS coils could be efficiently applied to recover commercially valuable materials and to improve environmental remediation efforts. Magnets for high-energy particle accelerators, magnetic resonance imaging, and energy storage systems may also be feasible in the liquid nitrogen temperature environment.

2. Wire Properties

The word "wire", as commonly understood [2], normally implies long length, flexibility and high current capacity. Not surprisingly, many of the "issues" that we identify deal with the very important goal of preserving these characteristics of the conductor.

2.1 Performance

The word "performance" applied to superconducting wire refers to the critical current density J_c of the wire. The early elemental (Type I) superconductors [20] were never of practical interest, mainly because they carried very little current; and a magnetic field of a few hundred gauss (0.03 tesla) would quench superconductivity completely. Type II superconductors have the very important property of having high J_c even in magnetic fields of several tesla [21]. All the HTS materials fall within the Type II category. Samples of YBCO, BSCCO, etc. from 1988-1990 were plagued with crystal imperfections and mechanical irregularities, and showed J_c values below 10 A/mm^2. The advantage of contemporary BSCCO wire is that it has $J_c > 1,000$ A/mm^2 (at sufficiently low temperatures and modest magnetic fields). YBCO coated conductors made via IBAD techniques have $J_c > 10,000$ A/mm^2 in short samples. RABiTS technology is equivalent in J_c in short samples, and may offer other advantages, which are further discussed below.

The high performance of these samples is due to very good grain-alignment, which in turn is due to the substrate conditioning achieved by IBAD and RABiTS. If the alignment of consecutive grains deteriorates (i.e., misorientation of adjacent grains by more than 5 to 10 deg.), the value of J_c drops sharply [10], and the material is no longer useful for high-current applications. One

objective of the second-generation wire program is to extend these coated conductors to very long lengths (> 1 km) while still preserving high J_c values.

It is far too early to forecast an outcome based on "either/or" IBAD/RABiTS methods. In 1997, it would be shortsighted not to devote some effort to technically well-founded, small high-risk, high-payoff ideas. However, after 1997, it should be possible to eliminate or scale back support of any HTS film-deposition techniques which cannot produce $J_c > 5000$ A/mm^2 (at 77 K and 0 tesla) on single crystals as they would not be acceptable in the multi-grain substrate.

The substrate technology is currently a technology driver as a separate entity, because many unresolved technical issues remain before 100-m or greater lengths of the substrate, ready for deposition of the superconductor, are available with the quality (texture, smoothness) required for YBCO deposition. However, the success of coated conductors also depends upon successful development and deployment of affordable processes for YBCO deposition. Whether or not a particular process will scale to commercial systems is the object of considerable debate within the technical community. Nevertheless, most industry-led teams are feverishly searching for high-rate, low-cost alternatives to the pulsed laser process. This roadmap accounts for the fact that the substrates may be ready for commercialization well before the superconductor process. It is this parallel path approach that allows for continued progress and broader access to "good" substrates for pilot plant runs that will be needed prior to introduction of YBCO "coated conductors" into the marketplace.

It is instructive to take the development of first-generation BSCCO wires into perspective in order to extrapolate the development cycle of second-generation wires. For example, the first synthesis of the BSCCO-2223 compound occurred in 1989. In early 1991, short lengths of less than 100 A/mm^2 wire were available (Figure 2.1). By mid-1996, kilometer lengths of wire with engineering current densities approaching 200 A/mm^2 had been produced, and at least one company had fabricated over 100 km of the wire during the previous 12 months. The estimated price (unreported, but estimated from industry teams currently working in the DOE program) of the pre-production wire delivered in 1995-96 to various systems' developers, ranged from \$1000-3000/kA-m, with typical I_c's of 20-30 amperes (77K, H=0) and piece lengths greater than 100 meters. However, YBCO coated conductors require a completely new type of production equipment and "thin film" processing techniques (common in the metallized can label, snack food bag, and recording tape industries but quite different from much of the equipment used to make BSCCO-2223 "OPIT" wires). This capitalization represents a barrier to the YBCO coated conductor development business that few companies can afford to overcome without strategic partnerships with other companies, the national laboratories, and universities. For example, estimates of the capital cost to install a pilot line for coated conductors range from as low as \$5 million to as high as \$50 million. Clearly, the selection of the "right" substrate and deposition technology has become an important consideration.

2.2 Real Wire Considerations

Increasing the thickness of the conductor film is an important issue. *Total* current, as contrasted to current *density*, is what is needed in practical applications, and so a high J_c must be accompanied by a large film cross sectional area in order to deliver the total current. Typically, thin films are perhaps 0.4 µm in thickness, so even a 1 µm film borders on the category of "thick". These conductors may require thicknesses (total) of 5 or 10 µm to achieve the total current needed (unless values of J_c can be increased substantially), and this introduces a new worry. As the YBCO

layer thickens, is there a possibility that mis-oriented grain growth will occur, defeating the purpose of the original textured substrate? Also, will film mechanical properties (cracks in YBCO film over 3-5 μm thick) similarly limit the overall thickness? It may turn out that 1 or 2 μm is the maximum practical thickness. Carrying out the experiments needed to answer these questions is one critical step along the roadmap.

Any real wire includes some "overhead" for insulation, etc., and therefore we distinguish between the critical current in the superconducting material itself J_c, and the "engineering" critical current J_e. For practical applications, the figure of merit is J_e, not J_c, because J_e relates to how much actual current flows through a real conductor with a certain cross-sectional area. In the case of BSCCO made by the Powder-in-Tube (PIT) method, the amount of silver surrounding the BSCCO reduces J_e compared to J_c. In the case of YBCO coated conductors, the thickness of the substrate and buffer may be ten times the thickness of the YBCO itself, in which case the reduction from J_c to J_e will exceed a factor of 10 -- the penalty for "overhead" is very severe. Among samples made thus far, a factor of 100 is typical.

Therefore, this aspect of the program plan demands the achievement of four simultaneous objectives: long length of thick film on thin substrates, while keeping excellent grain alignment so that J_c remains high. Only in this way will J_e be sufficient to win out over competing conductors.

Referring to the issues chart (Table 2.1), for the first two lines (J_c and J_e), the dots indicate that J_c is an issue in the HTS material only, whereas J_e is an issue involving the substrate, buffer and the superconductor. The dots throughout the remainder of Table 2.1 were placed through similar reasoning for each issue.

Table 2.2 enumerates the properties of wire needed for a variety of applications. The second column shows the required current density of the wire, that is, J_e. This has important consequences. The numerical values of $J_c > 1,000$ and $J_e > 100$ A/mm^2 together imply that the HTS material must be at least 10% of the final wire cross-sectional area. Allowing a very thin insulation of a μm or two, this implies that the substrate can only be about 8 times thicker than the YBCO layers (2-5 μm, one on each side) -- perhaps 32 to 80 μm, compared to 50-125 μm today. This is going to be a difficult goal to achieve; and when manufacturing considerations are added (see Section 3 below) the severe mechanical strains may stand out as a major obstacle.

Furthermore, the *uniformity* of cross-section of both the buffer and the YBCO layer must be maintained to within some tolerance over the full length of the wire. In one sense, this is an element of manufacturing quality control, but it must be understood that variations in thickness uniformity affect J_e.

From the viewpoint of setting priorities, this combination of J_c and J_e numerical goals for long length practical wires is necessarily first. Below 100 A/mm^2 (J_e), we simply do not have practical wire. The second-generation wire program cannot compromise or water-down these goals. Because this is such a critical objective, *the likelihood of reaching a show-stopper is higher here* than in any of the other cluster of issues.

2.3 Magnetic Properties

Moving down to slightly lower priority issues, we consider the cluster of issues relating to magnetic behavior. It must be recognized at the outset that the competing product BSCCO may be adequate [22] for transmission lines, where the self-field is a small fraction of a tesla. Here we

are interested in operating at liquid nitrogen temperatures in magnetic fields of several tesla where BSCCO cannot operate.

In the first generation of wire, the sheathing material (silver) is non-magnetic. Using RABiTs, the first thing to note is that the substrates are often magnetic materials (e.g., nickel). Therefore, it is important to investigate the interactions between substrate and HTS in a magnetic field. (The dots in Table 2.1 so indicate.) It is a matter for experimental measurement to determine how the critical current $J_c(H,T)$ will behave when finite magnetic fields are applied to the combined coated conductor. Alternative choices of substrate (Hastelloy, stainless steel) may be examined to minimize adverse effects of external magnetic fields, although it is expected that these alloys may be difficult to align by rolling.

The subject of AC losses is complex and depends on the application. Experimental measurements are usually needed to verify theoretical expectations. Often differences between theory and experiment are interpreted in terms of conductor non-uniformity. Generally, AC losses are associated with changing magnetic fields. Self-field losses are those which occur due to the magnetic fields produced by the conductor acting on itself. Other losses are caused by the interactions of the different components of a system. For a tape conductor, the orientation of the magnetic field is important; the losses are usually larger when the field has a significant component normal to the plane of the conductor.

Eddy current losses are due to currents induced in normal metal as the result of time-varying magnetic fields. In conventional motors, generators, and transformers, for example, these losses are reduced by the use of laminated steel for the magnetic circuit and the use of thin conductor strands for the copper conductors. The steel is formulated with high electrical resistivity and minimum magnetic hysteresis in mind. Transposition of the copper conductors also can be used to reduce eddy currents. Second generation coated conductor technology offers reduced eddy current losses relative to BSCCO powder-in-silver tube technology due to the higher resistivity of the nickel or nickel alloys (relative to silver) used to support the superconductor. However, the ferromagnetism of pure nickel may lead to hysteretic losses if it is used as a substrate.

The AC hysteresis losses in the superconducting phase are generally described theoretically with the use of the well-known Bean and Norris models. The physical picture is that changes in the externally imposed magnetic field cause flux penetration into the superconductor. The losses are proportional to the frequency, since the loss per cycle is fixed, and are also proportional to the inverse of the critical current density. Since second generation conductors are expected to have high critical current densities, the inverse dependence of loss on J_c is a beneficial aspect. Initial measurement of self field losses on YBCO coated conductors seem to be encouragingly low and probably interpretable with the Bean/Norris model [23].

The geometry of a broad tape conductor may lead to deleterious circulating currents which move along one edge of the tape and return along the other edge. Such currents can be reduced by reducing the width of the tape or by introducing narrow non-superconducting regions so that the tape is effectively a group of narrower tapes.

To date, only a few measurements have been made of AC losses in HTS materials [24,25]. Some applications have designed around the AC problem [26], as in the HTS electric motor project, where the synchronous rotation of the HTS windings allows them to "see" a predominantly DC field. That won't work in other applications, such as transformers. For many cases, the AC losses of the actual engineered conductor must be measured early in the design stages, so that the operating penalty in energy losses is well-understood.

In the case at hand, the close proximity of a thick magnetic material (the substrate) demands that attention be given to the determination of AC losses [27,28] for tapes processed by the RABiTS approach. It is expected that AC losses may not be a problem with IBAD tapes. The effect of hysteresis in nickel and related alloys cannot be ignored. In this program plan, we recommend that a sub-program of AC-loss measurements be carried out, using whatever length RABiTS samples are available. If some particular construction of the conductor is going to be so lossy as to have no useful application, it is better to find that out early in the development effort.

Among other things, the AC-loss measurement program should be accompanied by a series of design calculations to figure out what amount of losses are acceptable in various applications. Once the baseline loss data for actual samples is in hand, the projection to estimated operating costs in practical devices should be a straightforward calculation.

2.4 Geometry

The geometrical considerations have mostly to do with the matter of *flexibility*. Truly useful wire will be bent in most applications [2], as shown in the column labeled "bend radius" in Table 2.2. In some cases, the bend radius is as small as 1 cm. The parameters of layer thickness, bend radius, bending strain, and tensile/compressive strain all come together under the umbrella of "geometry".

At first, it seems desirable to coat the substrate with a very thick film of YBCO. Doing so increases J_e, hopefully without sacrificing J_c. But this is not assured. The total current flowing in the full conductor is the key figure of merit; if very thick films accumulate defects and then succumb to poor grain alignment, for example, the anticipated J_e will not be realized. Maximizing the useful film thickness is a key goal, and exploring the limits of various deposition technologies is an important part of this program plan.

The variation of J_e with film thickness needs to be experimentally investigated in this program. The consequences of the findings could be severe. If it should turn out that only thin films carry high current, then a change of direction toward multi-layer sandwich conductors would be indicated. If J_c remains uniform as thickness increases, then the program should proceed to attempt to maximize the YBCO layer thickness of the manufactured product.

Bending: When a layer is 5 μm thick, and bent on a radius of 5 cm, the strain is of the order of 1 part in 10^4. However, these coated conductors including substrate may have total thicknesses as large as 100 μm, and it is the total conductor that will be bent around the specified radius in each application. It is unrealistic to say "bend it only one way, not the other" in an attempt to spare the YBCO layer from strain. Accordingly, in Table 2.2, we indicate strain tolerances of a few parts in 10^3, rather than 10^4. These numbers are not too severe for YBCO.

The tension/compression strain is a relative of the bend strain. Results specific to coated conductors are in agreement with the bulk results [10,33]. Data from TCSUH by Salama and co-workers [29] has clearly demonstrated that, like all ceramics, the HTS materials can tolerate much higher strain in compression than in tension [30]. In contemplating a film coating one kilometer long, it makes sense to think about ways to "pre-stress" the substrate, so that the YBCO is in compression during normal handling of the finished conductor. It is well to remember that no one has yet made a thin film 1 km long; stretching or buckling of the film as the substrate changes shape may prove to be a very difficult obstacle.

2.5 Monitoring of Information

The above categories of research do not involve the kind of specialized technical features that manufacturers keep proprietary. Therefore, it is anticipated that progress in these categories will be widely disseminated through technical meetings and refereed journals.

As one example, it can be observed that progress in both IBAD and RABiTS technologies have been sufficiently encouraging to warrant the attention of prospective wire manufacturers. At the moment, Oak Ridge [11] and Los Alamos [31] teams seem to be slightly ahead of European researchers [32,33], and Japanese researchers are reporting progress toward longer length coated conductors [34,35]; but we cannot become complacent about our knowledge here. The contributions of distinctly separate groups are often crucial to finding a pathway to a research objective. Keeping track of all these pieces is an important step in moving from research results to ultimate commercial success.

2.6 Diagnostics

Both the materials and the process technologies envisioned here are exceptional, compared to ordinary chemical and metallurgical substances. Thus it is plausible to expect that there will be entirely new physical measurements that will provide useful information about the behavior of the YBCO-substrate combination. Accordingly, this plan envisions a series of studies in the laboratory which are explicitly aimed at discovering those exceptional diagnostic measurements. Techniques such as ellipsometry, RHEED, PREEL, Raman spectroscopy, and many other instruments [36] will be part of the repertory of measurements. New and innovative ways of measuring the important parameters of HTS wires will be needed for robust manufacturing processes. An expanded discussion of diagnostic technology as it relates to process control and measurements is contained in Appendix B.

3. Manufacturing Considerations

In any manufacturing process, there are trade-offs among process speed, down-time, cost, and yield. It no longer suffices to have everything scrutinized by the researchers; to be profitable, a manufacturing process must run in a highly automated way. Controllability of the process is paramount, for without it, profits will vanish rapidly. When manufacturing criteria are imposed upon the products of a research laboratory, a major step upward in difficulty is taken. The DOE superconductivity program recognized this reality in the first generation of conductors, and this plan anticipates the same requirements for second-generation conductors.

3.1 Process Scaling

Researchers are able to make short lengths of conductor using either IBAD or RABiTS methods. However, *useful wire* needs to be a kilometer or more in length for most power/utility applications. Clearly, the foremost objective of the scale-up effort here is to increase the length of product. The requirement is for about 4 orders of magnitude improvement in 5 years. This is the most ambitious goal in the entire DOE superconductivity program. This cannot possibly be done by a research laboratory alone, which is why this program is a cooperative one with industry from the start.

Experiments to demonstrate scale-up of film deposition will be costly. Therefore, careful preparation is required to qualify film deposition processes for prototype manufacturing. In the near

term, focus should be on demonstrating high rate, high quality film deposition with small-scale modified research apparatus. The stages of process qualification include:

(1) Prepare HTS films thicker than 1 µm, with J_c above 10,000 A/mm^2 (77 K, 0 T), on single crystal substrates. This figure corresponds to I_c greater than 100 A/cm of tape width. (The 5-year goal is to reach a 100 A wire operating at liquid nitrogen temperatures and 5 T, which may be achieved with thicker films and/or further improvements in J_c.)

(2) Demonstrate on a lab scale similar technology on metal substrates, using suitable buffer layers and a high temperature superconducting coating.

(3) Determine the maximum specific film deposition rate (µm per minute) which can be achieved. Identify the barriers (defects) which limit high rate growth, and work to eliminate them.

(4) Determine the window in various processing parameters (such as substrate temperature, working pressure, deposition rate, etc.) which is available for high quality film growth.

(5) Proceed to continuous processing of short tape samples (less than one meter in length). Experiment with progressively thinner substrate tapes, and determine appropriate film and substrate thicknesses. Considerations here are film mechanical properties, the observed dependence of I_c on film thickness, and difficulty handling very thin substrates.

(6) Based on the results of steps 1 to 5, plan a pilot plant facility, compare estimates of manufacturing costs with the requirements of the various applications, build a facility and produce "samples".

Up to the present time the IBAD and RABiTS processes for producing textured substrates, and the pulsed laser deposition technique for buffer and HTS film deposition, are the techniques of choice for laboratory investigation of small prototype samples. This choice is based on the fact that the resulting prototype samples satisfy criteria 1 and 2 above, and work is in progress on items 3 to 6. However, reaching the cost goals at which applications will be attractive will most likely require process improvement, process modifications, and process substitutions. For example, the film deposition steps for both the IBAD and RABiTS substrate preparation alone, are presently too slow. Pulsed laser deposition of the thick HTS layer is also prohibitively slow and must be radically improved or be replaced by some other process such as e-beam evaporation, MOCVD, or wet chemical processes (e.g., sol gel).

In the following paragraphs, we address some of the specific issues involved in scale-up.

3.1.1 Thickness

Manufacturing of coated conductors requires that high-quality films be deposited on substrates at high rates. The superconducting layer will be relatively "thick", in the range of 1 to 10 µm; whereas buffer layers, diffusion barriers, passivation layers, etc., can be thinner. Since the thinnest commercial metal tape substrates (e.g., of oxidation-resistant nickel superalloys) are about 1 mil (25 µm) in thickness, it is important (as stated in Section 2 above) to obtain a thick superconducting film.

The maximum permissible thickness is not yet known. Thicker layers are stiffer and more prone to fracture; they are also more prone to delamination due to differential thermal expansion during processing. However, it is clear from more than one study [10,37] that films several μm thick may be acceptable.

3.1.2 Speed

The *speed* of the production process is of paramount importance; "production time" is an interchangeable term. The manufacturer's question comes down to: How many meters of wire were produced today? Most YBCO films fabricated to date have been deposited over cm-sized substrates during a period of a few minutes to hours. In these laboratory studies, the primary consideration has been film quality, not deposition speed. Straightforward scale-up entails deposition on larger area substrates, and increasing the power to the deposition-apparatus to boost rates until film quality just begins to degrade.

As noted previously, scale-up for tape conductor manufacturing requires high rate film deposition of buffer layers, superconducting layers, and any passivation layers, such as a top silver layer. Small-scale laboratory deposition rates are typically only a few angstroms per second; the growth of a μm thick film then requires roughly an hour. Since one would like to deposit at least a few square meters per hour, the size of the deposition equipment would need to be rather large. An order of magnitude increase in deposition rate can permit the deposition chamber dimension to be reduced by a factor of 3, and the cost of the chamber correspondingly falls by a factor of about 30. Thus, there is a significant incentive to increase deposition rates. For very thin buffer layers, the deposition rate is less critical.

Each film deposition process will have some maximum rate, beyond which defects or other problems such as supplying source material or removing by-products are limiting. For example, diffusion of the depositing atoms on the growing film surface requires time. If the deposition rate is too high, then some atoms will not have time to diffuse to their proper sites. Research is ongoing to determine what these maximum rates are for various processes.

A few specific examples can indicate some of the increased rates achieved so far. For pulsed laser deposition, YBCO coatings have been formed at rates higher than 1 μm per minute. This is done by increasing the pulse rate of the laser. Unfortunately, the size of the laser plume is such that only a small number of square centimeters of substrate can be coated by a single laser, so that larger lasers and multiple lasers would appear to be required. With photo-assisted MOCVD, rates on the order of 1 μm per minute of YBCO have also been achieved [38]. In this case, the present high cost of the precursor metal-organic compounds is presently an issue. Electron-beam co-evaporation is believed to have considerable potential for large area deposition at high rates. One recent paper [39] reports a technique for coating substrates up to 9 inches in diameter with YBCO, at nominal rates of 24 nm/min. For co-evaporation, an important issue is the accurate balance of evaporation rates from the separate Y, Ba, and Cu sources.

For relatively thick YBCO films, grown at high speed, it can be expected that oxygen annealing will require attention. In small scale growth, the films are generally cooled slowly from a high deposition temperature (above 700°C) in oxygen. During this cooling oxygen is absorbed by the films (at 400° - 500°C), and the non-superconducting tetragonal phase is converted to the superconducting orthorhombic phase. Since this oxygen diffusion is a relatively slow process, particularly in the c-axis direction, it is anticipated that spools of YBCO tape may need to be batch annealed to ensure adequate oxygen uptake.

For IBAD buffer layer growth, the present laboratory rates (a few angstroms per second) are too slow for straightforward scale-up, since the required thickness is nearly a μm. Researchers need to speed up the deposition, or produce good biaxial orientation with much thinner layers, or both. Recent results from Stanford [40] on ultra-thin IBAD MgO buffer layers are promising in this regard.

The buffer layers for RABiTS can apparently be rather thin, certainly less than a μm. The maximum buffer layer growth rate may be determined by the fact that fully epitaxial growth must be maintained. The texture from the metal substrate must be passed through each buffer layer to the HTS layer.

At a minimum, any viable manufacturing technique must produce a few square meters per hour. This contrasts with current laboratory rates of a few cm^2/hour. Thus, film-deposition rates must increase by about four orders of magnitude. (Despite the high areal rate, the amount of YBCO to be deposited is only a few tens of cm^3/hr.)

We are starting from thin-film techniques, which are used under laboratory conditions to produce centimeters of material; we want to get to an automated technology churning out thousands of kilometers annually. That is a huge step. We have to face squarely the possibility that "you can't get there from here" in an economically acceptable manner.

The phrase "industry-driven program" is nowhere more pertinent than here. Companies who are prospective wire manufacturers have to call the shots when discussing scale-up. The national laboratories can understand basic properties, and can innovate process methods, but they are not geared to doing full-scale manufacturing.

3.1.3 Cost

An issue closely related to *speed* is *cost*. A key question is whether long lengths can be manufactured economically. In Section 5 we present a few simple calculations to illustrate how the cost of capital equipment must be amortized over the total wire produced. In fact, that amortization can be represented as a cost-per-unit-length, which underlines the importance of having a manufacturing method which produces long lengths of conductor quickly.

The cost of materials used in the coating process will also have a significant impact on the final product cost. Some processes require exceptionally pure materials and quality control will be an issue in the delivery of these materials in large quantities. Hopefully larger quantities will provide economical benefits as opposed to the small lots being purchased for lab scale work at present.

For the process of actually depositing the YBCO film, some of the equipment being contemplated is very expensive. At the research level, pulsed laser deposition is used to produce the YBCO films, because pulsed-laser deposition preserves the chemical stoichiometry of the material being transferred from target to substrate [41]. The favorable results on short samples were obtained by this route. However, serious production may likely demand some other cheaper, faster method of deposition. Electron-beam deposition is being studied [42]. Macroscopic coating techniques for thick films, such as the Doctor-blade method are known, but the question of preserving good grain alignment must be addressed. Right now there is no candidate technology that is known to be cost-effective. Therefore, this issue stands out as a critical item on the roadmap, which must be solved through innovation by the participating teams of national labs, universities and wire manufacturers.

3.1.4 Quality Control

Every industrial process depends for its commercial success on a very dependable quality-control system. Generally, the computer algorithm for real-time process control uses certain actuators to regulate parameters of the process line. To do so, feedback of real time data from on-line sensors is needed. To assure stability of the process, the combination of sensors, control algorithm, and actuators is arranged into a closed feedback loop to keep parameters within a safe operating area.. It is instructive to examine how modern conventional commercial vacuum film deposition is performed as an example [43]. This article discusses systems for thermal evaporation from resistively heated boats, electron beam evaporation, magnetron sputtering and plasma-enhanced chemical vapor deposition. A typical example is the deposition of a thin metal coating on a polymer film (the "web") for the manufacture of capacitors. Substrate thickness ranges from 20 μm down to less than 1 μm. Metal coatings 30 nm thick are deposited on 800 mm wide substrates at rates of roughly 10 meters per second. Immediately after coating, as the film moves to the rewinding drum, the coating quality is monitored with suitable diagnostic equipment. In this case of simple metal films, optical transmission, optical reflectance, or sheet resistivity are often monitored.

HTS film and buffer layer coating processes are more complex, since the materials are more complex. For YBCO film deposition the substrate temperature is one of the key parameters requiring control. Temperatures which are too high cause film roughness and contribute to undesirable interdiffusion of film and substrate materials; temperatures which are too low lead to nucleation of a-axis grains instead of the desired c-axis orientation.

As another example, consider the electron-beam co-evaporation of yttrium, barium, and copper metals, which in the presence of oxygen, can produce YBCO films. The deposition rate of each of the metals must be controlled to produce the correct 1:2:3 ratio of the cations. One proposal for tightly controlling these rates is to use atomic absorption spectroscopy to monitor the individual rates [44].

Several questions immediately arises: what sensors? what measurements? what parameters? what actuators? Here is where the diagnostic tools discussed in Section 2 above have their impact. Based on what is *learned* through laboratory measurements with diagnostic tools, it will be possible to select certain physical phenomena that are quite sensitive to critical properties of the tape or wire being produced. Then a relatively simple measurement package can be placed on-line which determines that property with sufficient accuracy to enable a control strategy to be implemented. In the later stages of this program, we envision partnerships (CRADAs) between industry and national laboratories to create a series of on-line measurements that will ultimately provide the necessary control strategies to make coated conductors at speeds that are cost-effective and profitable.

3.1.5 Splices

The requirement that YBCO coated conductors be a kilometer or more in length is a major manufacturing challenge. Furthermore, there are applications that need much more than one kilometer. Therefore, it is necessary to investigate the matter of connecting pieces of this wire. Two complementary issues arise here. What is the minimum lot length that is acceptable as output of the process line? And how much current capacity is lost when two pieces are spliced together?

Clearly, if splices can be made with very low losses, shorter production runs become tolerable; and conversely.

In the past, splicing of either YBCO or BSCCO has not generally been considered "successful", because the junctions had mismatched grains and thus had sizable losses. Research ongoing now [45] which includes careful grain alignment will hopefully yield splices of better quality and lower losses. Fairly early in this program, some specific numerical goals for acceptable splices should be established and incorporated into the collection of milestones. For some applications a few low resistance joints may be acceptable.

3.2 Endurance

In Table 2.1, a series of issues are listed under the heading "endurance", including encapsulation, shelf life, thermal cycling, etc. These are all issues of importance to wire manufacturers, and will certainly affect profitability somewhere downstream. Presumably scientists from the national laboratories may be valuable advisors in addressing them. However, none of these issues are likely to produce a "show stopper", and therefore do not appear to pose obstacles along the roadmap. Here we give them very little attention, preferring to allow private-sector partners to consider these issues in due time.

3.3 Life Cycle Costs

Referring once again to Table 2.1, certain issues have been identified under the category of *Life Cycle Costs*. Specifically, the operating costs of using this wire (as compared to competing choices of wire), as well as the capital costs of manufacturing equipment, each need to be considered. The total cost of transmitting current is a combination of factors. For wire to be sold at a profit, that total cost must be less than the value added by the application in which this wire is used. Otherwise, no truly commercial sales will occur, and the only uses will be in projects supported by subsidies of some kind.

Basically, these issues are matters of competitive costs, because at some price level, YBCO will cease to be the technology of choice. Section 5 deals with competing technology, including the capital cost of manufacturing (Section 5.1) and the advances in other wire technologies (Section 5.2). Considerations within this category are handled best by the private sector, where making decisions about investing in various technology options are a standard part of doing business. In this program, we expect that as research objectives are met and manufacturing concepts start to receive attention, the private-sector partners will contribute the necessary analyses of life-cycle costs.

4. Milestones

This program plan defines a roadmap (Figure 4.1) that will lead to practical coated conductors for specific applications. Any good roadmap has checkpoints along the route, to provide feedback and evaluate progress. The same is true in this program plan. Our expectations are that gradually, over a period of several years, a product will evolve that is considered a true, useful conductor. Enroute to that, a number of subordinate technical accomplishments may be defined.

4.1 Wire Properties

Table 4.1 proposes a collection of numerical objectives for the various properties of the YBCO coated conductor, to be reached by the annual dates indicated. These numbers apply to a "generic" second-generation wire. By contrast, the "final-state" properties of wire serving various specific applications are displayed in Table 2.2. Comparing those two tables reveals that the "generic" wire is fairly representative of the properties needed for most applications.

If the numerical goals in Table 4.1 are reached on time, then there will be wire at the end of the tunnel. These numbers are certainly challenging; but they are generally agreed-upon by technical experts at the participating national laboratories and corporations [46].

4.2 Participation Milestones

Because the long-range goal of the second-generation wire development program is to end up with wire for sale commercially, it is reasonable to expect that corporate partners will become more active in the program as the technical milestones are reached. Their level of interest is a criterion for evaluation by DOE management. Accordingly, certain milestones for private-sector participation are proposed here, to allow a measurement of that interest.

By the start of FY1999, there should be significant private sector participation in place (i.e. CRADAs) which focuses on YBCO coated conductor development. No specification is made here of who the corporate team members should be; the likely partners envisioned today may have a "full plate" of other interests when FY1999 gets here, and other partners will step up instead. However, if interest in forming CRADAs is very weak by then, it is a signal that a cornerstone principle of the program is lapsing, and that condition calls for re-evaluation of the entire effort. In all likelihood, the level of CRADA activity will reflect the achievement of technical milestones toward real wire.

By the start of FY2001, the participation of private companies should reach a level that will enable industry to ramp up to a manufacturing plant a year or two later. Table 4.2 is a summary of cooperative agreements industry has on the "Second Generation" wire. Once again, this level of interest will easily happen when (not "if") the technical milestones are achieved.

5. Competing Technologies

There are very real constraints on the allowed cost of any new product, and these constraints constantly tighten with improvements in alternative methods of reaching the same objective. HTS coated conductors are no exception to this rule.

5.1 Upper Limits

For any product, there exists an upper limit on price, above which sales vanish. For many products now in commercial use, the manufacturing cost of the first few units was so high that no one but the military had a deep enough pocket to afford it. The C5A military transport plane comes to mind; eventually it evolved into today's commercial airliners. But the front end cost was far too high to attract venture capital. Closer to home, the modern MRI machine (containing a superconducting magnet) is standard equipment in many hospitals now, but only a decade ago these machines were expensive research tools. MRI was implemented on a wide scale only because the "value added" associated with medical care is considered very high; *and* because nearly all medical bills are paid by a third party (often Medicare = the federal government).

When we consider power applications of superconductors, neither national defense nor health care stands ready to justify a high price. The utilities who will be the ultimate customers for second-generation wire have other choices, including the status quo (i.e., using copper wire). Replacement of existing technology will only occur when the total costs (capital plus operating) are substantially lower and the risk is no higher.

Suppose, hypothetically, that when all the losses are rolled together, expensive YBCO coated conductors have perhaps 2 % of the resistance of copper wire at 77 K. The higher capital cost for the YBCO can be weighed against the higher operating cost for copper. "Capitalizing" an operating cost can be done by treating the annual operating cost as an annuity [47], and asking how much principal is required to produce that cash flow (at typical interest rates). If one assumes an "annualized cost of capital" rate of 10%, then in order to generate $100,000 annually, it is necessary to set aside $1,000,000. Thus an annual operating cost increment of $100,000 balances against a capital cost increment of $1,000,000. When a different rate is chosen, the numbers shift around somewhat, but the idea is the same.

Calculations of this type need to be carried out in order to find the crossover points at which HTS conductors cease to be attractive. Such calculations will refine the existing ball-park estimates about the acceptable price of wire, by including comparisons between copper and HTS conductors with realistic operating parameters.

Once an upper limit on price is established, that in turn will constrain the choices of manufacturing techniques. Consider a simple example:

Suppose a hypothetical manufacturing process requires $30,000,000 worth of plant and equipment to make 100 km of wire each year, and the wire carries $I_c = 10^3$ amperes (= 1 kA). Is this an acceptable cost? Starting with an opportunity-cost-of-money of 14%, then a capital investment of $30 million is equivalent to an annual outlay of $4.2 million. That outlay must be amortized over the 100 km of wire produced. Therefore, $4.2 x 10^6 / (10^5 m x 10^3 A) = $ 0.042 / A-m, or $42/kA-m. This is the equivalent cost of capital alone. We have not even mentioned either the raw materials cost, depreciation of the capital equipment, or the annual operating cost of the factory. All of these drive the $42 figure still higher. (The target price is $ 10/kA-m.) This price is far too high. To solve this dilemma, either the machinery must be a lot cheaper or run a lot faster. The upper limit on wire price has thus set certain constraints on the manufacturing process.

Coming at it from another direction, if the value of a superconducting tape 1 cm wide is roughly $ 1/meter, then a small manufacturing plant with a value of $ 30,000,000 must produce several million meters of tape per year to justify the investment.

Detailed cost analysis of this type is always done by entrepreneurs before committing their resources to a process. Within this program plan, we anticipate that an important contribution of the private-sector partners will be to consider all the financial aspects carefully.

5.2 Alternatives

Alternative technologies also advance over time, and so YBCO coated conductors will be challenged by improvements in competing products. At the moment, the cost figure of $10/kA-m is a convenient target for thinking about manufacturing HTS wire, but that number is likely to decline in the years ahead. There are several different categories of competitive improvements.

5.2.1 Refrigeration

Ten years ago, the only temperature-choices were 77 K or 4 K, and there was no reason to think about operating at intermediate temperatures such as 20 K or 50 K. Today, with advances in Gifford-McMahon refrigerators [48], it is easy to run at such temperatures, and so BSCCO wire enjoys a substantial useful range. However, from Figure 1.5 it is obvious that YBCO enjoys a decided performance advantage over BSCCO, Nb_3Sn and NbTi materials, at a given temperature and magnetic field. The refrigeration system employed will be determined to a large extent by the application used. In some cases it will be necessary to use liquid nitrogen, or helium, for practical reasons.

5.2.2 BSCCO

Advances in BSCCO wire compete with YBCO coated conductors. To date, BSCCO-2212, which has $T_c = 80$ K, carries very little current in magnetic fields of 1 tesla or more, and its applications are confined below 30 K. However, BSCCO-2223 $[(Pb,Bi)_2Sr_2Ca_2Cu_3O_{10}]$ has a higher transition temperature of 105 K, and there is hope that improvements in pinning will enhance its usefulness in the 40 - 60 K range. Researchers have pioneered an improved form of PIT (Powder-in-Tube) technology, which features inserting a silver wire in the center of the tube, so that the BSCCO-2223 forms an annulus. A key research discovery here was that nearly all the current is carried in the boundary region of BSCCO close to the silver. Hence, by increasing the fraction of such boundaries in the cross-section, the critical current J_c increases. Of course, BSCCO wire is still very sensitive to the alignment of the magnetic field (H ∥ ab vs. H ∥ c axis) [49], so this is no panacea. Still, it illustrates that there is progress in BSCCO technology.

5.2.3 ReBCO

Over the horizon, the choices are not necessarily limited to YBCO and BSCCO. Today, the thallium compounds are very difficult to work with, because the high vapor pressure of thallium contaminates apparatus. Moreover, TBCCO lacks the important property of micaceousness that allows BSCCO grains to be so well-aligned. Hence the prospects for making TBCCO wire are considered bleak today. However, it may be that the IBAD or RABiTS processes will produce substrates on which TBCCO crystals will form with good alignment. In that case, TBCCO-1223 [50,51,52] may become a competitor to YBCO coated conductors. Thallium films with J_c's of 10,000- 100,000 A/mm^2 have been demonstrated by SUNY-Buffalo and by Midwest Superconductivity on single crystal $LaAlO_3$. The Tl-1223 precursors were deposited by PLD. Thallium films develop texture in the post-annealing step, so epitaxy during precursor deposition is not required (as is the case for YBCO deposited by PLD), a potential advantage for thallium. The higher T_c may also be important to certain power applications. With a suitable lag time for conducting basic research, the same speculation may be offered about the mercury [53] compounds.

5.3 Implications

At our present early stage, we need not take a position on any of these future possibilities. When the time comes, the private sector companies who will eventually be the manufacturers of various forms of superconducting wire will be better able to judge economic trade-offs. Right now we are dealing with a research program, and our roadmap strives to define a set of milestones that can enable future decisions to be made. One possible decision is always to say "Give up and stop";

but the more likely scenario is that as milestones are reached, the need for specific further development work will be better understood, and the details of the road map will be refined.

6. Technology Requirements and Priorities

Every program of research ultimately is made up of a collection of technical activities, each focusing on one particular component of the overall goal. This program, spanning several national laboratories and involving many industrial collaborators, contains a wide variety of technical tasks. In this section we briefly discuss some of the highest priority technical questions, and then present three tables that list the tasks cited by the Steering Committee as essential to achieving the final product: practical YBCO coated conductors.

The first set of questions deals with how the performance of the YBCO film depends upon:

- YBCO Deposition rate

  The highest rate at which epitaxial films can be grown on the buffered substrate is not known. Rates of the order of 1 μm/min or higher are needed for commercial purposes. Microstructural studies must accompany transport critical current density measurements to establish the limit to the YBCO growth rate.

- YBCO Coating thickness

  The engineering current density, J_e, and the economic viability of the superconducting tape will be driven by the thickness of the superconductor. Beyond a certain thickness value, presently not well-known, the J_c may deteriorate to a point that additional YBCO is not valuable to the structure. The effect of rate of deposition also plays a role in the J_c versus thickness equation. In addition, compositional variations as a function of deposit thickness, substrate texture, substrate smoothness, and chemical contamination from underlying layers at the YBCO deposition temperature are all expected to play a role in determining optimum thickness. Mechanical properties and stresses will depend on thickness and these will be issues to consider in determining the maximum thickness.

- Magnitude of composition variation away from stoichiometric Y-123

  The composition window can be an important driver, depending on the deposition process being used. A certain composition window, with yttrium or copper slightly rich and the barium deficient, is known from the literature to be acceptable. However, the outer boundaries for this composition window on coated conductors have not been established. Naturally, a wider window simplifies the design of systems with feedback composition control, such as electron beam evaporation. The effects of the degree to which the YBCO is off-stoichiometry on deposition rate and total thickness must also be determined.

A second category of questions deals with the metal substrate type and quality (textured nickel, commercial Hastelloy, etc.) The type of substrate will affect the overall cost and utility of the superconducting tape. For example, the high-purity nickel used for RABiTS may cost more per unit weight than commercial Hastelloy. Certain applications may require a non-ferromagnetic tape substrate, ruling out today's RABiTS altogether. Finally, the pure nickel used for RABiTS is extremely soft at the YBCO deposition temperature, making design and operation of a continuous, non-contact heating and deposition system challenging due to handling issues. The development

of strengthened, non-magnetic metal substrates might be an important aspect of any technology roadmap for RABiTS. The effects that substrate materials have on AC losses need to be determined for the coated conductor configurations being developed. A trade-off study yet to be undertaken would compare the costs of preparing the metal substrates used by both the IBAD and RABiTS processes.

Third, the selection of any deposition technique necessarily implies certain other subordinate technical questions. There is no perfect technique. For example, when contemplating MOCVD, pulsed laser deposition or high-rate sputtering, there are major worries about the ultimate deposition rate achievable. Pulsed laser deposition has a very high capital equipment cost, and target/plume stability issues; high-rate sputtering raises questions of compositional control; MOCVD has major issues with precursor quality and cost.

Electron beam evaporation, by contrast, faces obstacles associated with melt pool stability, on-line composition monitoring (by atomic absorption), an activated oxygen delivery system, control-algorithm development, the beam density at the substrate, and several other variables.

Wet chemical deposition techniques have been demonstrated with J_c's of 10,000 A/mm^2 [54] on single crystal substrates and, if applicable to metal substrates, could present an attractive alternative to vacuum-based deposition. This choice could result in a cheaper overall substrate if buffer layers were deposited entirely in ambient conditions.

There are certain technology issues that are common to all techniques: for example, substrate heating and handling at 700°-800°C. Also, there is a need for physical modeling of the deposition process to optimize composition control, coating uniformity, process yield, and so on.

6.1 Summary of Principal Technical Issues

This program plan recognizes at the outset that the development of second-generation conductors is to be an industry-driven program. The ultimate goal of commercial success will be achieved by clever and practical innovators, and this will occur downstream. At this writing, it is only possible to enumerate examples of the type of technical obstacles to be overcome - first at the R&D level, and later at the manufacturing level. Here we present tables 6.1 and 6.2, listing selected (but not exclusive) technical issues of high importance for both the substrate and the superconducting layer development. In addition, there are wire-related issues that must eventually be addressed, especially by the private sector partners as they move toward commercialization. These issues are listed in table 6.3.

7. Summary

The foremost objective of the second-generation wire development program is to establish enabling coated conductor technology from which the private sector can proceed toward commercialization.

In the sections above, we have described the various issues that must be addressed in order to reach the desired goal of commercial wire. In this section, we try to put all these pieces together into a unified story that explains the roles of DOE, the national laboratories, and the private sector partners.

Figure 7.1 is a sketch of the progress envisioned in this program. We begin with a basic understanding of how to coat substrates, but no capability to make wire. In the early stages ahead, the work to be done is research, and will be done predominantly by the national laboratories; the

private sector companies will provide guidance, based on their knowledge of what must lie ahead in any manufacturing process. As the program meets its early milestones, we anticipate that additional CRADAs will form, and private-sector participation will equal that of the national labs (i.e., 50/50, as in normal CRADAs). At an intermediate point, probably in FY1999, one or two preferred methods of making long lengths of coated conductors will emerge. After that, the CRADA mechanism will continue as pilot production lines become established. During this later phase of the program, company trade secrets will become the central distinguishing features of competing processes; the national lab scientists involved will respect confidences throughout this phase, just as they have already done as they worked on developing BSCCO wire. Finally, in future years beyond the scope of this plan, private-sector companies will refine their own preferred manufacturing techniques to make truly commercial wire.

For practical wire, the engineering critical current J_e is much more important than the critical current in the YBCO layer J_c. J_e is a smaller number, owing to the inclusion of the thickness of the substrate, the buffer layers, and an outer coating of insulation. Even if that insulation is only a one-mil thick coating of varnish, still these layers of "baggage" may add up to nearly 100 μm, compared to a YBCO film thickness of 1, 2 or at most 5 μm.

The penalty in the J_e / J_c ratio is severe. Certain applications (electric motors, for instance) require engineering critical currents above 200 A/mm^2; therefore, researchers need to strive diligently to maintain J_c above 10,000 A/mm^2 in the YBCO film. Also, while getting the film thickness up near 5 μm is obviously desirable, it is equally important to maintain very high J_c for the entire thickness of the film -- a point which has not yet been demonstrated. At the wire manufacturing companies, emphasis must be placed on ensuring the survival of a very thin substrate (one mil = 25μm), and encapsulating the finished product with a very thin coating. At the end of the tunnel, numerical goals in these categories may well determine the success or failure of these coated conductors for several applications.

Challenges remain in maintaining outstanding high temperature superconducting properties obtained on short samples of YBCO coatings on biaxially textured substrates while increasing film deposition rates on longer tape lengths in a continuous approach. To be commercially feasible, the coated conductors must be produced in an effective manner that is reliable for large scale production. Los Alamos has been developing IBAD and PLD units to deposit on one meter long tapes and has now achieved J_c(77K) values of over 1,500 A/mm^2 on selected regions of these longer tapes. It is expected that considerable progress will be made in this area during the near future. Both the IBAD and the RABiTS processes must be scaled up to longer lengths: the underlying substrates must be produced in a cost-effective manner with the quality (biaxial texture) over the full length and width necessary for long-range, high-current conduction. Another issue is the joint between lengths of coated conductors: can the joint be engineered in such a manner that there are few high-angle grain boundaries at the intersection? In addition, strengthened, non-ferromagnetic base metal strips for use in high-magnetic field applications of RABiTS may need to be developed. Finally, passivation coatings to protect the wire from failure due to exposure to moisture or other contaminants must be developed.

Figure 7.2 presents a time frame over which the many identified issues may be pursued in the years ahead. Clearly, the greatest emphasis is on the development of long lengths of conductor; as stated above, the improvement needed is 4 orders of magnitude, so this is the central make-or-break

issue of the entire program. The numerical accomplishments indicated in Table 4.1 are shown along the time-lines for conductor development.

Subordinate issues of concern to manufacturers are not immediately important until the question of making long lengths is under control. However, several other issues, including diagnostic measurements to learn how to control the process, proceed in parallel during the early stages, because they directly affect whether or not the intended long lengths can ever be realized. It is particularly important in the early stages to settle questions of magnetic behavior, thermal compatibility, and strain tolerance, which could conceivably seal the fate of certain pathways.

Appendix C is a compendium of the statements throughout the text above which designate specific research activities that need to be done. There are also a number of management decision points, which follow from the output of each of these activities. The most important decision points are keyed to the numerical goals stated in Figure 4.1; these goals focus on the most difficult and challenging aspects of the second-generation wire program. If this set of goals is met, other problems will diminish in significance.

This program plan attempts to specify a roadmap to guide the transition from the state of R&D today to the eventual production of commercially successful wire. The roles and expectations of national laboratories and corporate partners alike are set forth in a balanced way that relies upon continuing cooperation among colleagues who share a common goal. It is not possible to guarantee success, but it is possible to proceed in a way that recognizes risks and obstacles, and faces them squarely. The progression described here from laboratory research to cooperation with industry (CRADAs) to wire manufacturing has built into it a high degree of optimism, without which R&D never even gets started. Nevertheless, there are sufficient checkpoints and feedback to enable management to monitor progress continually and to allocate resources optimally.

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Program Activities Flowchart

	FY 1996	FY 1997	FY 1998	FY 1999	FY 2000
	1	2	3	4	5

Wire Technology

Short-length wire process and micro-structure technology

Milestone: YBCO/BSCCO/TBCCO $J_c=1\times10^4$ to 2×10^6 A/cm^2 $I_c=100$ Amps

Milestone: Short-length wire with $J_c=40,000$ A/cm^2, self field

Milestone: Improved wire sheaths / cost competitive processes

Milestone: Short-length wire with $J_e=80,000$ A/cm^2 at 77K, self field

Milestone: Short-length wire with $J_e=25,000$ A/cm^2 at 77K, 1T

Systems Technology

Long-length wire component and device technology

Milestone: Coils with 3-5 T operating field at 20-40 K

Integrate improved wire and processing technologies

Milestone: Coils with 2-5 T operating field at 40-77 K

Milestone: 1-km wire with $J_c=50,000$ A/cm^2 at 77 K, 0T

HTS wire manufacturing fully supported by private sector

Figure 1.1 Program activities flowchart from *Superconductivity for Electric Systems Program Plan (FY 1996-FY 2000).*

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Ion Beam Assisted Deposition

Vacuum Chamber

Assisting Ion Beam Gun

35.3⁰

Hastelloy Tape

YSZ Target

Deposition Ion Beam Gun

LANL IBAD

c-perp, in-plane aligned YBCO

(100) CeO$_2$

(100) YSZ

Hastelloy
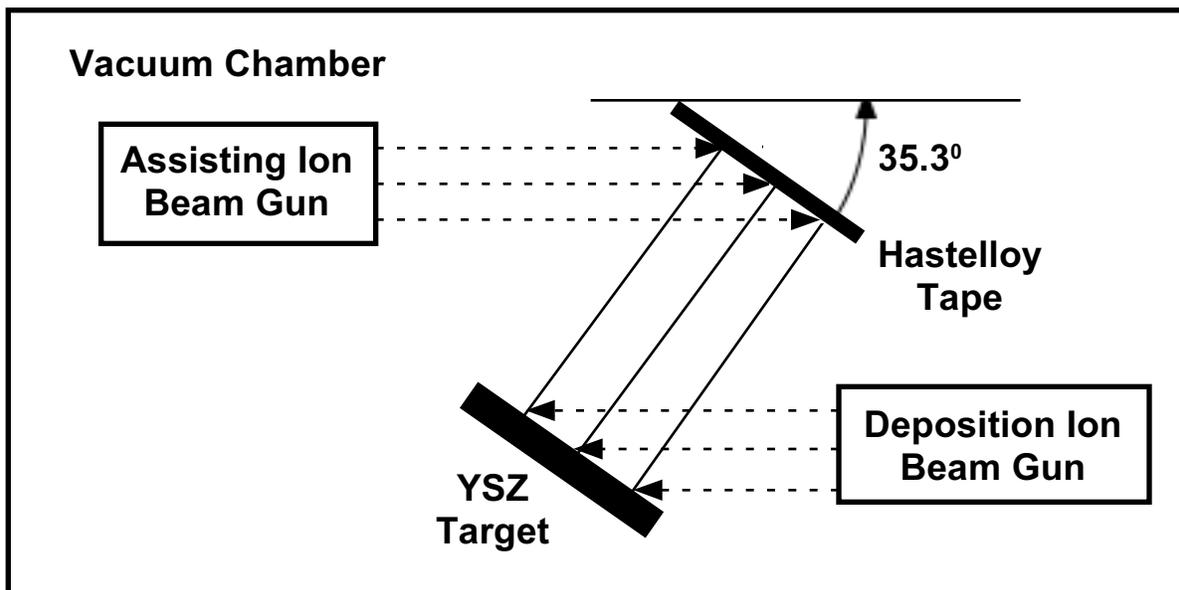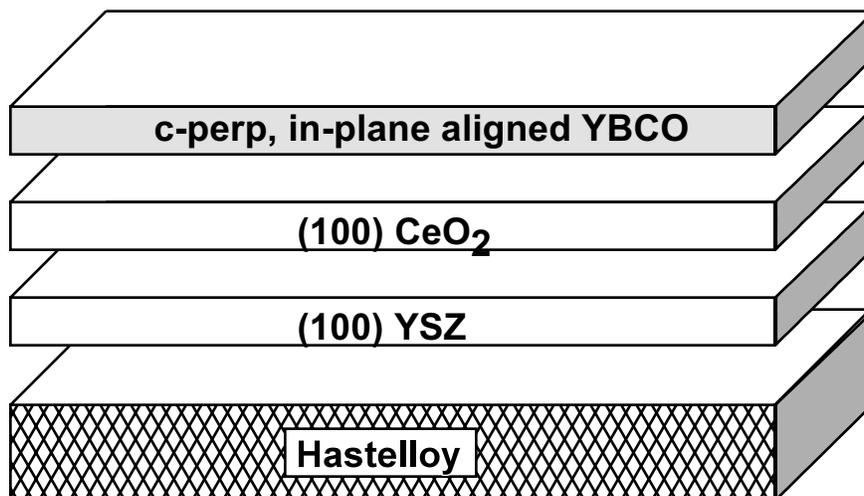
Figure 1.2 Architecture of Los Alamos IBAD substrate with buffer layers and YBCO coating.

Rolling-Assisted, Biaxially-Textured Substrates

Ni Rod

Ni Tape

Anneal

Buffer Layer Deposition

ORNL RABiTS

c-perp, in-plane aligned YBCO

(100) YSZ

(100) CeO$_2$

Biaxially-textured, rolled (100) Ni
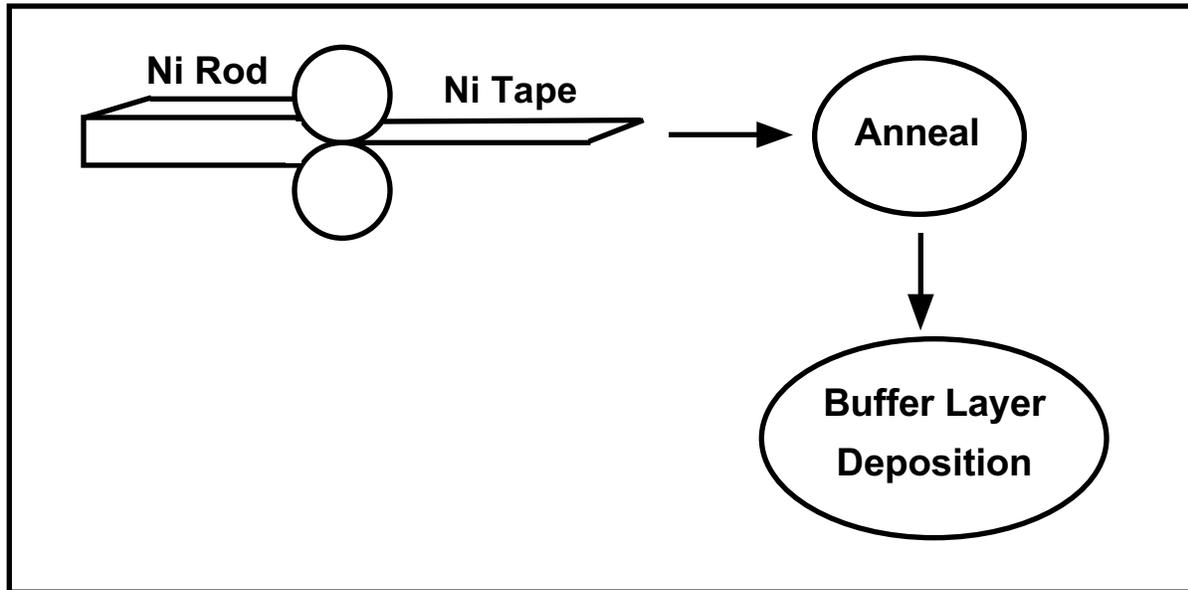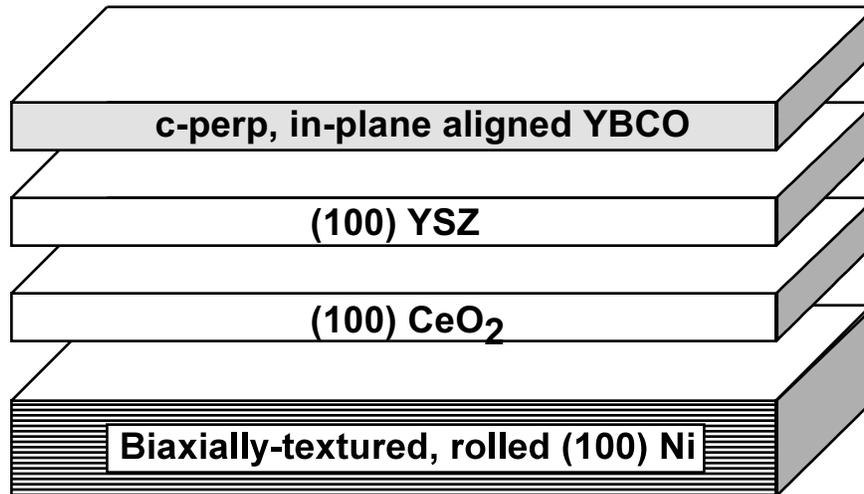
Figure 1.3 Architecture of Oak Ridge RABiTS substrate with buffer layers and YBCO coating.
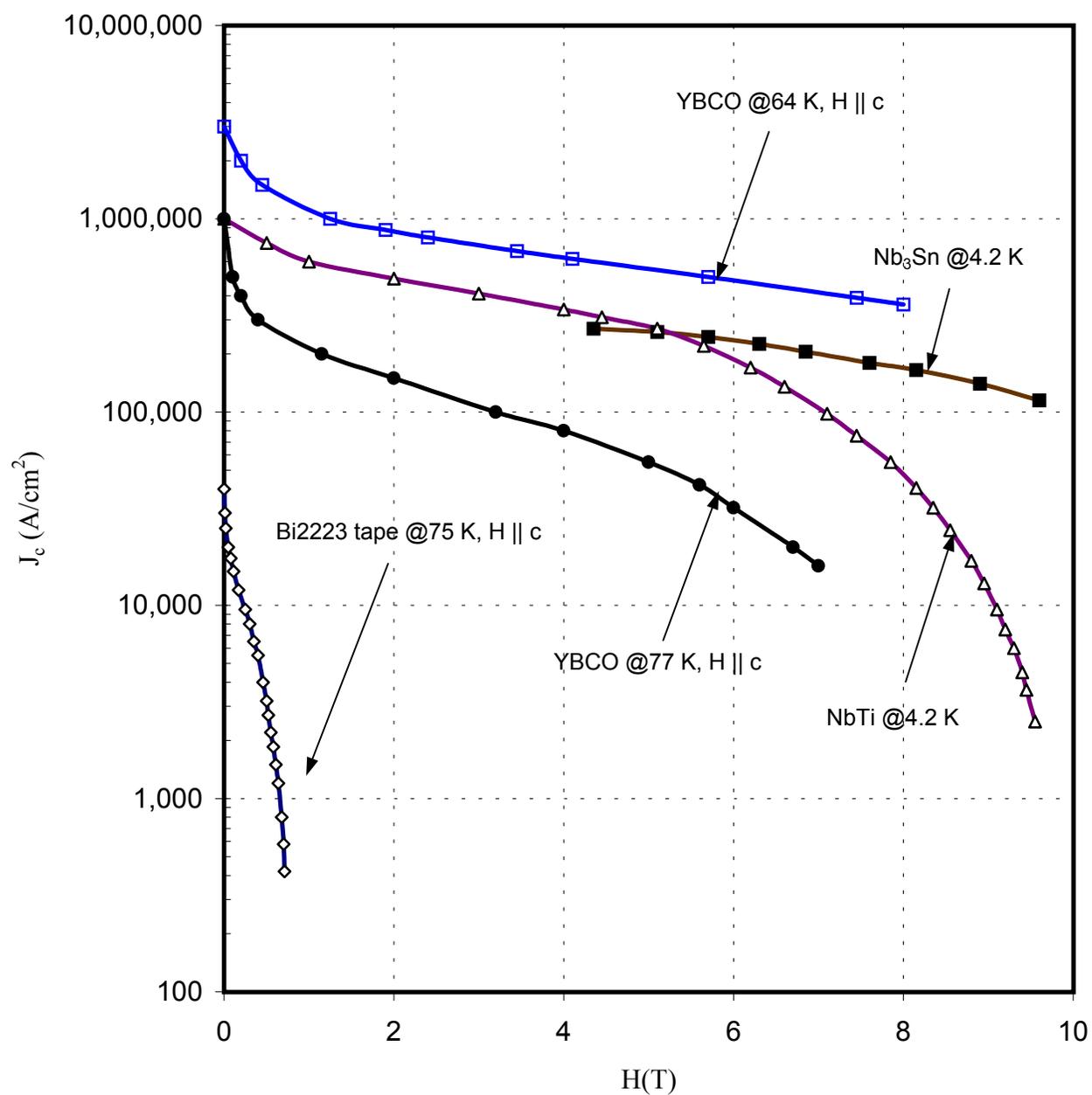
Figure 1.4. Magnetic field dependence of the critical current density for a range of short-sample YBCO conductors produced using either IBAD or RABiTS substrates. These data are compared with typical values obtained for NbTi and Nb$_3$Sn wires at 4.2 K.
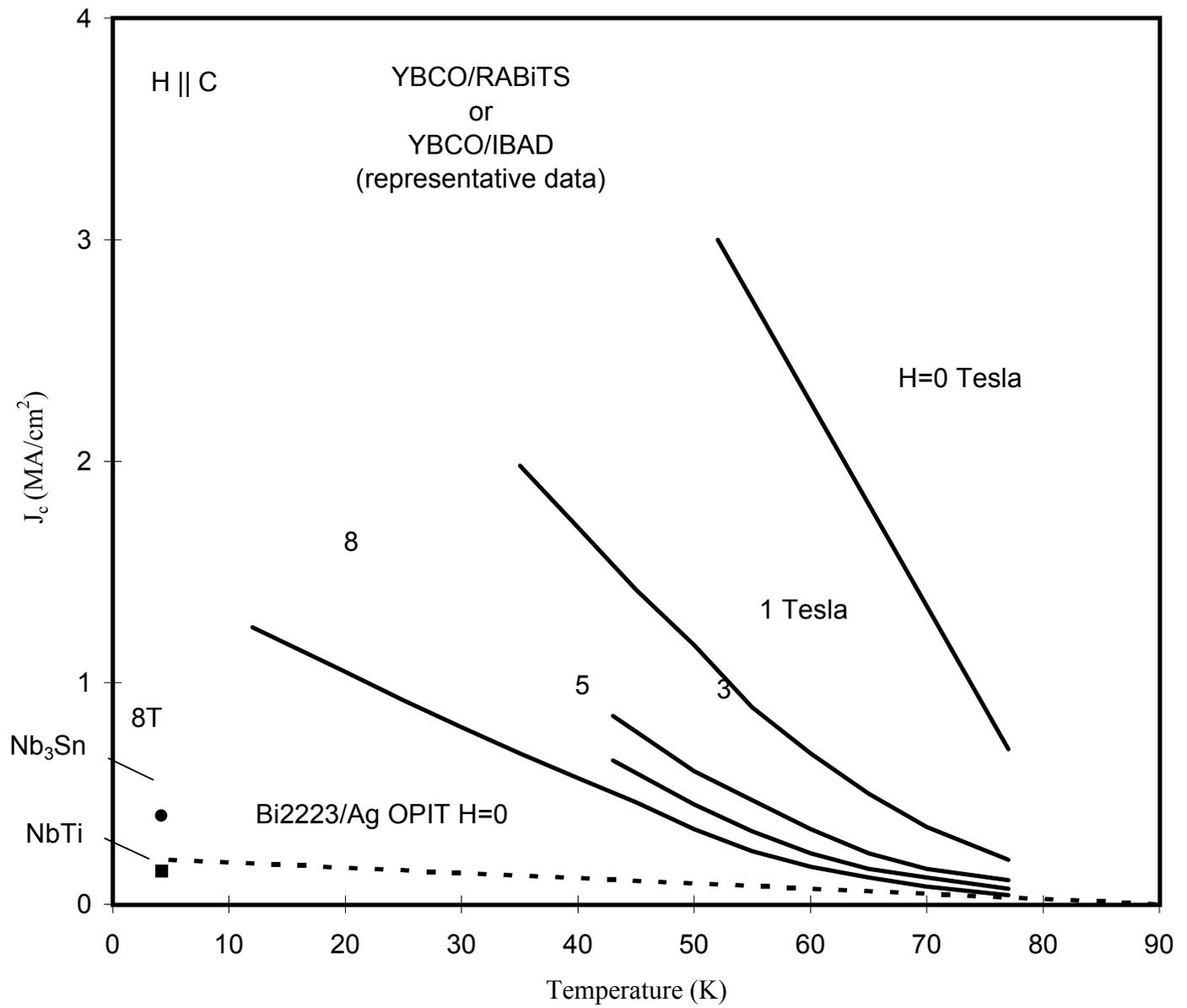
Figure 1.5 Temperature dependence of the critical current density for representative short-samples of YBCO coated conductors produced using IBAD or RABiTS substrates.
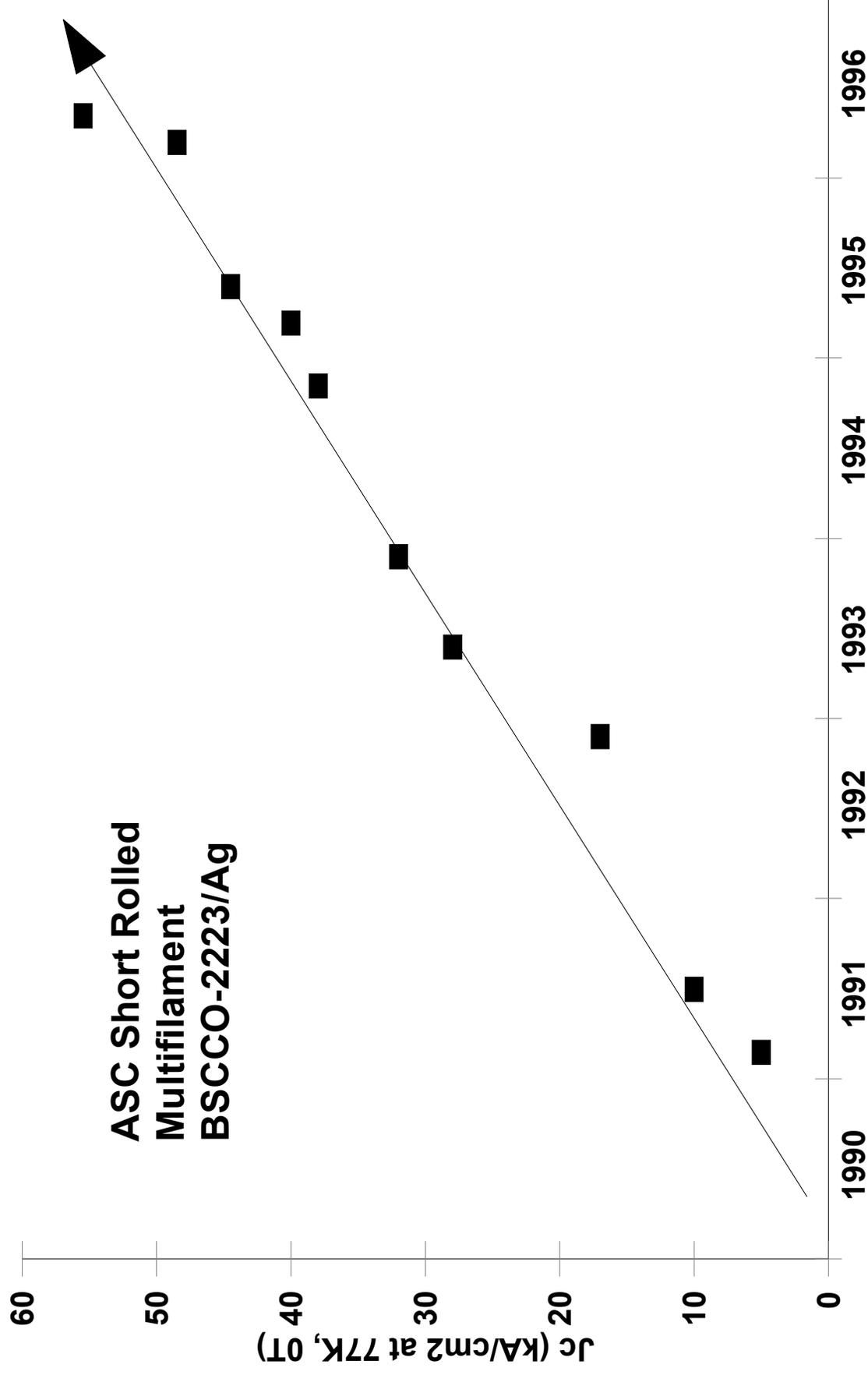
Figure 2.1 Timeline of BSCCO-2223 OPIT wire development for short-sample, rolled, multifilamentary wires. (courtesy of American Superconductor Corp., August 1996)

Table 2.1 Issues for Development of Practical Coated Conductors for High Field Applications

| Issue	Conductor			Manufacture	Application
	Substrate	**Buffer**	**HTS**		
1. Preserving Current Capacity					
$J_c > 1000$ amperes/mm^2 (B = 5T)			●		
$J_e > 100$ amperes/mm^2 (B = 5T)	●	●	●		
2. Magnetic Properties					
Behavior of J_c (H,T)	●	●	●		●
AC Losses	●		●		●
3. Geometry					
Thickness - Optimum	●	●	●		
Strain (bending)	●	●	●		●
Tensile/Compressive Strength	●	●	●	●	●
4. Scale-up					
Production Time				●	
Chemical Compatibility			●	●	
Effect on Environment				●	
Cost	●	●	●	●	
Quality Control	●	●	●	●	●
Minimum Lot Length				●	●
Splices					●
Thermal Expansion Mismatch		●	●		
5. Endurance					
Encapsulation	●	●	●		●
Effect of Environment				●	●
Maintenance				●	
Shelf Life				●	●
Thermal Cycling					●
6. Life Cycle Costs					
Operating Costs of:					
This Wire					●
Competing Wire					●
Capital Equipment Costs				●	

Table 2.2 High Temperature Superconducting Applications: Wire Performance Requirements

Application	Commercial HTS Wire Requirements								
	J_e (A/mm²) 77K, self-field	Cost/tape ($/kA-m)	Field (T)	Temp$_{op}$ (K)	I_c/tape (A) 77 K self-field	AC loss (mW/A-m)	Bend Radius (m)	Strain (%)	Wire Length (m)
Fault-Current Limiter	10 – 100	30->10[a]	.3 - 3	40->65	100	0.4	0.15-0.05	0.2-0.4	200-1000
Motor	100	10	4	>25	300	NA[b]	0.05	0.2-0.3	1000
Generator (100 MVA)	10	10	4-5	20->65	100-200	NA[b]	0.1	<0.2	500-1000
Cable	10 – 100	10-100	<0.2	>65	>30[c]	0.15	0.01	>0.4	100-1000
Transformer	10 – 100	20->5	0.15	20-65	200	0.25	0.1-0.2	0.1	250-3000
High Field Magnet	10 – 1000	5->1	>20	4.2->65	300-500	NA	0.01	0.5	500-1000
Magnetic Separator	1	10	2-3	77	500	NA	0.5	0.2	1000

Table Developed at 1997 DOE Wire Development Workshop and Represents Consensus of Industrial Participants.

[a] Arrow represents cost decrease necessary from pre-commercial to final cost necessary to enable commercial devices.

[b] For current field coil design.

[c] Current for individual wires; full cable assembly will carry 3-5 kA.

Underlined items represent highest priorities for each application according to panel participants.
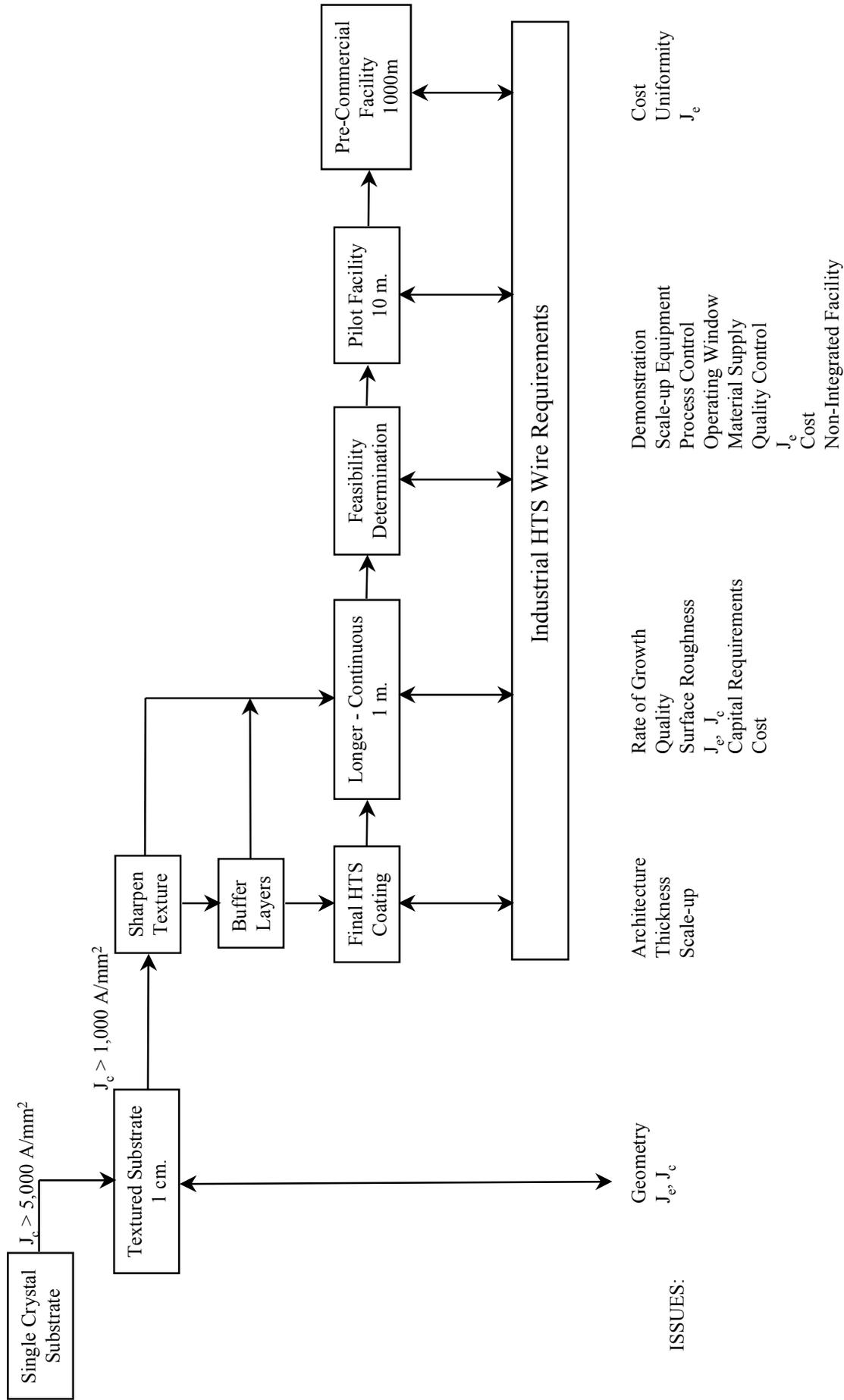
Figure 4.1 Technical Roadmap for the Development of Practical Coated Conductors

Single Crystal Substrate

$J_c > 5,000$ A/mm^2

Textured Substrate 1 cm.

$J_c > 1,000$ A/mm^2

Sharpen Texture

Buffer Layers

Final HTS Coating

Longer - Continuous 1 m.

Feasibility Determination

Pilot Facility 10 m.

Pre-Commercial Facility 1000m

Industrial HTS Wire Requirements

ISSUES:

Geometry
J_e, J_c

Architecture
Thickness
Scale-up

Rate of Growth
Quality
Surface Roughness
J_e, J_c
Capital Requirements
Cost

Demonstration
Scale-up Equipment
Process Control
Operating Window
Material Supply
Quality Control
J_e
Cost
Non-Integrated Facility

Cost
Uniformity
J_e

Table 4.1 Overall Roadmap Technology Characterisitics

Characteristic	1997	1998	1999	2000	2001
J_c (A/mm^2 @5 Tesla H∥c)	100	500	500	1000	1000
J_e (A/mm^2 @5 Tesla H∥c)	10	50	50	100	100
Length (m)	1	1	100	100	1000
I_c (Amperes @5 T)			50	100	100

Table 4.2 Summary of
Cooperative Agreements with Industry on "Second Generation" Wire
(as of November 12, 1997)

Partners	Type of Agreement	Technology Description	Agreement Budget ($K)
American Superconductor Corporation/ORNL	Phase I SBIR	Phase I SBIR task - Develop nonvacuum buffer layer deposition process for textured substrates	75
American Superconductor Corporation/EPRI/LANL	Strategic Alliance	Develop and assess a variety of coated conductor technologies for industrial scale-up	5,000
IGC/ANL	Pilot Center Agreement	Develop MOCVD coating of YBCO	350
MicroCoating Technologies/ORNL	2 Phase I SBIRs	Combustion-CVD process development for buffer layers and YBCO deposition	150
Midwest Superconductivity/ORNL	Phase I SBIR	YBCO/RABiTS with conductive buffer layers	75
Midwest/Westinghouse/ORNL	CRADA	RABiTS research and development using MOCVD	1,440
Oxford Superconducting Technology/ORNL	CRADA	RABiTS research and development using PLD	300
Plastronic/ORNL	Phase I SBIR	Develop alternatives to pure nickel substrates	75
3M/Southwire/LANL/ORNL	CRADA	Research and develop IBAD and RABiTS-based YBCO conductors	3,817
		Total	11,282

Table 6.1 Priorities: Substrate Technology Needs

Highest Priority:
- Produce lengths greater than 100 meters with requisite smoothness, texture, and thickness uniformity.
- Improve texturing to improve grain angle alignment
- Develop other substrate and buffer layer options, including non-magnetic materials.
- Scale up buffer layer deposition rate.
- Develop thinner buffer layers and metal substrates.
- Develop vacuum deposition process in addition to PLD.
- Develop a materials science understanding of the buffer layer function.

Secondary Priority:
- Specifications for acceptable buffered substrates (to include AC loss consideration).
- Develop non-vacuum or wet chemical process for buffer layer deposition.

Table 6.2 Priorities: Superconductor Technology Needs

Highest Priority:
- Produce coatings on substrates of lengths greater than 100 meters that meet industrial wire requirements.
- Develop alternate film deposition technologies.
- Develop means to achieve higher J_c values for a given thickness.
- Higher J_c, J_e and I_c.
- Faster and lower cost HTS deposition methods.
- Determine conditions (process specific) needed for growth of YBCO coatings that meet customer requirements.

Secondary Priority:
- Demonstrate 2-sided YBCO deposition.
- Develop better adhesion and mechanical properties.
- Develop deposition methods for HTS materials other than YBCO.

Table 6.3 Priorities: Wire Manufacturing Technology Needs

Highest Priority:
- Reduce Cost.
- Scale up to continuous processing.
- Improve Reliability.
- Develop in-situ monitoring tools for substrate and superconductor manufacturing processes.
- Develop passivation/insulation layer(s).

Secondary Priority:
- Develop splicing/joining technology.
- Improve mechanical properties.

Figure 7.1 Coated Conductor Technology Development Roadmap

Activity/Issue	1997	1998	1999	2000	2001	2002
Critical Current Density, J_c		100	500		1000 A/mm^2	
Engineering Current Density, J_e		10	50		100 A/mm^2	
Length		1		100		1000 meters
Diagnostic Measurements						
Magnetic Properties: J_c(H,T)						
AC Loss Measruements						
Strain Measurements						
Continuous Production Speed						
Manufacturing Cost (per kA-m)					$10	
Quality Control						
"Endurance" Parameters						
Life-Cycle Cost Reduction						

Figure 7.2 Second generation HTS wire program time schedule. (Current density values are at liquid nitrogen temperatures at 5T)

HTS COATING DEVELOPMENT

1. Material

The reason for focusing the efforts on YBCO is based on its high irreversibility field (H_{irr}) at 77 K. For operation at liquid nitrogen temperature YBCO is preferable to BSCCO which until now has been the most popular wire considered for electric power applications. YBCO retains high critical currents in strong magnetic fields because there is stronger coupling between its copper-oxygen planes than that in BSCCO. YBCO has much better intrinsic flux pinning than BSCCO, but it has poor intergranular current flow because of weak links. For YBCO, as well as other rare earth based oxide materials (REBCO), the role of oxygen content on fundamental superconducting properties is noted. The proper oxygen partial pressure in cooling sintered YBCO and REBCO materials is imperative for promoting the transformation from the tetragonal to the orthorhombic phase, the latter having a T_c of 92 K.

For conductor applications, two other cuprates show promise. Thallium barium calcium copper oxide, known as TBCCO, has two candidates-Tl-2223 and Tl-1223 with T_c's of 110 K and 125 K respectively. TBCCO has properties that fall between those of YBCO and BSCCO. It has links that are stronger than those in YBCO, but its flux pinning is not as good as that of YBCO and it is not obvious what buffer layer material would be used. TBCCO has caused some concern about toxicity, but will be used if it has good performance and price.

2. Processing

Initial hurdles of processing YBCO to satisfy high current applications were overcome by the melt texturing process[1] developed in 1988. This process yielded pseudo-single crystals that had transport current densities of 1,000 A/mm^2 in self-field and 10 A/mm^2 at 77 K and 30 T[2,3]. These results led to high level of optimism in the research and applications of HTS materials although single crystals are not the objective for wires due to inadequate flux pinning. The melt texturing process involves the peritectic melting and solidification of the 123 phase. When heated above the peritectic temperature, solid Y-123 decomposes into solid Y-211 and a liquid phase that is rich in Ba and Cu. Slow cooling through the peritectic temperature allows the recombination of Y-211 and the liquid phase to form melt textured Y-123. In this compound the rate of recombination and solidification is extremely slow since it is dependent on the rate of diffusion of yttrium from Y-211

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[2]K. Salama, V. Selvamanickam, and D.F. Lee, in "Bulk Materials (Processing and Properties of High-Tc Superconductors 1) edited by S. Jin (Singapore: World Scientific, 1993) p 155.

[3]J.W. Ekin, K. Salama, and V. Selvamanickam, Nature 350, 26 (1991).

to the melt, which was found to be very small[4,5]. This is a serious drawback of melt textured YBCO compound which severely restricts its application.

It was recently shown[6] by the LANL Group that thick YBCO films can be deposited on flexible metallic substrates. In this procedure, an Ion-Beam-Assisted-Deposition (IBAD) process is used to deposit a biaxially textured yttria-stabilized zirconia (YSZ) buffer layer onto nickel-based substrates. Later, a YBCO thick film (2 μm thick) is deposited by pulsed laser deposition (PLD) onto the YSZ layer. The biaxial texture of the YSZ buffer layer is also present in the YBCO thick film and is crucial in inhibiting the presence of large-angle grain boundaries, since it was observed[7] that the in-plane J_c decreases exponentially with increasing misalignment. Typical YBCO/YSZ/Ni thick films, with an average of only 6 degrees of in-plane misalignment, have critical currents above 10,000 A/mm^2 in self field and 77 K.

A group at ORNL has announced a method called rolling-assisted biaxial textured substrates (RABiTS) which results in near-perfect substrate bi-axial texture. This system, which may include buffer layers on the metal substrate, produces surfaces aligned within 2 degrees. Current densities greater than 10,000 A/mm^2 have been achieved in films of thickness 1.0 μm. YBCO technology currently being developed at Los Alamos and ORNL promises to extend the range of application of high-T_c wires, especially if the substrate thickness can be reduced and the HTS film thickness increased.

Both approaches (LANL and ORNL) use PLD or laser ablation for depositing the HTS film on the textured substrate. There are other methods of laying down the HTS layer that show promise. The group at the University of Houston has shown that photo-assisted metal organic chemical vapor deposition (PhAMOCVD) could be used for YBCO thick film deposition at high growth rates (8000 Å/min) with J_c approaching 10,000 A/mm^2. Initially demonstrated on single crystal substrates, the technique is now being extended for HTS deposition on substrates prepared by IBAD or those substrates textured by rolling[8]. For a photo-assisted process, the optimum light source (e.g. quartz-halogen lamp?) has to be found. Possible configurations, i.e. horizontal or vertical-flow modes, would have to be considered. Data or empirical equations relating growth rate to precursors, light intensity and flow rate would be useful. If data is absent, it would have to be generated and fitted to rate equations in order to predict performance in continuous or batch operation. Even then, the MOCVD process has several problem areas which need to be addressed. These are: deposition/loss of HTS material at very low pressures on unwanted wall areas, non-uniformity of film coating, control of stoichiometry, use of costly and probably toxic organometallic compounds, and involved subsequent heat treatment.

Other approaches that could be considered are listed below:

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[5]T. Izumi, Y. Nakamura, and Y. Shiohara, Adv. Supercond. 3, 733 (1991).

[6]X.D. Wu et al., Appl. Phys. Lett. 65, 1961 (1994).

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[8]A. Ignatiev et al., 10th Anniversary HTS Workshop on Physics, Materials and Applications, Houston, March 1996.

Sol-gel processing
Dip coating/metal organic decomposition
Aerosol/spray pyrolysis
Electro-deposition
Electrophoresis

Each of these will now be described along with their merits and drawbacks. Table A-1 shows J_c results achieved to date with these processes. In analyzing the approaches, the following factors are considered:

(1) Type of starting material used. These include,

- Commonly used organometallic/inorganic precursors, as well as non-aqueous solvents to carry them.
- Desirable features for precursors, as well as solvents, such as availability, purity, stability, ease in preparing coating material, environmental concerns, potential of causing film defects, and cost.

(2) With regard to candidate coating processes, the analysis will address

- Type of substrate studied/required and potential for producing in a continuous mode
- Areas of concern related to operation, corrosion, product quality, waste management, toxicity etc.
- Limitations for scaling up to continuous wire manufacturing and possible solutions to resolve them, and overall economics
- Desirable features in ideal coating processes

Sol-gel Processing:

Organic salts of Cu, Ba, Y are prepared in suitable organic medium and then treated with water to form gel. The gel containing desired stoichiometry of precursor salts is deposited by spin or dip coating on suitable substrate or buffer at room temperature in absence of air and moisture. The coated substrate is pyrolyzed in air between 600°-800°C. To get desired film thickness, coating and pyrolysis steps are repeated a few times. Areas of concern include poor gel/precursor structure, and the fact that organometallic salts containing copper are not easily available. The method could have potential for continuous processing at an overall low cost if repetitive coating is eliminated, and simple and widely available organometallic salts are used which do not need extensive preparation steps to make precursor gel.

Table A-1. Critical current Density as a Function of Different Conductor Coating Techniques

Conductor Coating Technique	Highest J_c Achieved (A/mm^2)*	Remarks	Reference No.
Sol-Gel	2,000	YBCO on YSZ with (100) Orientation	1
	190	Tl-1223 on Silver Foil	2
Metal Organic Chemical Vapor Deposition (MOCVD, CVD, PE-MOCVD, etc.)	50,000	YBCO on LaAl0$_3$ with (100) Orientation by PE-MOCVD	3
	23,000	YBCO on LaAlO$_3$ with (100) Orientation by MOCVD	4
	1,400	YBCO by LS-CVD on Platinum and Amorphous YSZ Prebuffer Layers (Deposited over Hastelloy C-276 Metal Substrate by Sputtering).	5
	63,000	YBCO on SrTi0$_3$ Single Crystal with (100) Orientation by OT-CVD	6
	200	YBCO on Polycrystalline Silver Foils by MOCVD	7
	2,500 (Unreproducible)	YBCO on Polycrystalline MgO Substrate by TC-CVD	8
Metal Organic Decomposition (MOD)	3,900	YBCO on SrTiO$_3$ with (100) Orientation by D-P Process	9
	10 (100 at 4K)	YBCO by Spin-Coating on Single Crystal of YSZ Using TFA Precursors	10
	- (5,000 at 4K)	YBCO by Spin-Coating on Single Crystal of SrTiO$_3$ With (100) and (110) Orientations Using TFA Precursors	10
	>50,000	YBCO by Spin-Coating on Single Crystal of LaAl0$_3$ With (001) Orientation Using TFA Precursors	11
Electrodeposition	3.6 (40 at 4K)	YBCO on 9.5 mol % Y$_2$O$_3$ Stabilized Cubic Zirconia with (100) Orientation Using Nitrates	12
	- (40 at 4K)	YBCO on MgO Single Crystal with (100) Orientation Using Nitrates (under constant potential)	13
	- (51 at 4K)	Same as above except under Pulsed Potential	13
	- (5 at 4K)	YBCO on Nickel Strip/Wire and Silver Wire Using Nitrates	13
	- (55,000 at 4K)	TBCCO on Silver-Coated LAO Single Crystal Orientation Using Nitrates	14
	550 at 76K	Under Pulsed Potential	14
Aerosol/Spray Pyrolysis	300	YBCO on Polished MgO Substrate Using Aqueous Nitrates	15
Electrophoresis	10-20	Silver-Coated (Sheathed) YBCO on Nickel Alloy Wire	16

* J_c reported at 77K and no field.

Metal Organic Decomposition (MOD):

Organometallic salts are prepared by reacting suitable metal salts (oxides or carbonates) with trifluoroacetic acid (TFA) or purchased in desired forms. In desired stoichiometry; these organometallic salts are dissolved in non-aqueous solvents. The solution containing organometallic salts is coated using spin/dip coating method on a suitable substrate. The coated substrate is pyrolyzed in air around 400°-500°C (if the precursors are acetalacetonates) or baked in air at about 200°C to remove water of crystallization (if the salts are fluoroacetates). To get the desired thickness, the coating, baking (or pyrolyzing) steps are repeated a few times. Substrates with desired thickness of precursor coating are then decomposed in He or N_2 containing water vapor at 400°-850°C for fluoroacetate precursors. In the case of precursors containing acetalacetonates, the coated substrate is heat treated in a very involved sequence around 750°C in the Ar containing low ($\sim 10^{-4}$ atm) to high (~ 1 atm) levels of O_2. After heating for desired length of time, the material is then cooled to room temperature or below 200°C in O_2 atmosphere. Areas of concern include the complexity of the heat treatment, and possible corrosion due to liberated HF if fluoroacetates are used. The method has potential for large scale continuous processing if heat treatment steps are simplified and expedited and can be carried out in a continuous or batch (wound on spool) mode, and if corrosion problem due to HF can be successfully resolved.

Electro-deposition:

The process uses nitrates of Y, Ba and Cu dissolved in organic solvents such as dimethyl sulfoxide (DMSO) or isopropanol (IPA). In a 3-electrode configuration, with $Ag/AgNO_3$ as a reference electrode, Pt as a counter electrode and the substrate in suitable form (Ni, Ag-coated MgO, ZrO_2, etc.), electro-deposition is carried out between -2.5 V and -4 V. The coated substrate is then heated in pure O_2 around 850-1050°C for 1 minute. The oxidized substrate is then cooled to room temperature in pure O_2. To get the desired film thickness of superconductor on the substrate, the deposition, annealing and cooling steps are repeated. Areas of concern include the possibility of incorporating sulfur when DMSO is used as solvent. Similarly, Ag can also enter the film from Ag-coated substrate. Electrical conductivity of non-aqueous solution is very low resulting in very low deposition rates. This method could lead to a low-cost and simple processing scheme if solution conductivity can be increased by choosing a better solvent so as to increase the deposition rate and thereby avoiding repetitive steps of deposition, annealing and cooling.

Aerosol/Spray Pyrolysis:

Aqueous solution of Y, Ba, Cu nitrates is prepared and then atomized (sprayed) using flowing O_2 or N_2 to coat suitable substrate (which can be YSZ, $SrTiO_3$, zirconia or polished MgO) held at ≥ 800°C temperature in air in about 5 minutes. The coated substrate is then heated in O_2 to 900°C for 5-120 minutes. The oxidized sample is then very slowly cooled to room temperature. To get the desired film thickness, the steps of deposition, heating and cooling are repeated. The disadvantages are that $Ba(NO_3)_2$ crystals are formed in the film, the heat treatment step is not fully resolved, the nitrates of Y, Ba and Cu decompose at different temperatures, and the desired stoichiometry in the superconductor film can not be easily maintained. Copper level in film is somehow enhanced. The method can be a potential candidate for large scale processing, if heat treatment and cooling can be simplified and time duration for that can be shortened, i.e., a single temperature needs to be selected for decomposition of all the nitrates, better control of film stoichiometry is possible, and densified film can be obtained by depositing the nitrate solution at a higher substrate temperature, so that higher J_c value can be achieved.

Electrophoresis:

Oxides and carbonates of Y, Cu and Ba are mixed in a solid phase and calcined and then ground to 0.5-10 μm size. Ground-up powder is then slurried in a non-aqueous medium. From a spool, a Ni-alloy wire or tape is drawn at a predetermined rate into a vertical column filled with YBCO slurry, where by electrophoresis, YBCO coating is formed. The coated wire is then sintered at 950-1030°C in O_2 for 1-30 minutes. The oxidized wire is then electrophoretically coated with silver powder slurry in a non-aqueous medium. The silver-coated wire is then sintered at 850-950°C in O_2 atmosphere for 0.2-10 minutes. The sintered wire is then wrapped over a spool and further oxidized in a batch mode in O_2 atmosphere at 400°C for 1-3 days. The resulting wire can be used as it is or in a multi-filamentary wire form. Currently the J_c obtained by this method is very low. The method has been already tested in a continuous mode (1 meter/min rate) by General Atomics (GA) in the past. However, to make it attractive, improvements in heat treatment and texturing methods have to be made.

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PROCESS CONTROL AND MEASUREMENTS

There are two levels of diagnostics. One is process control, which must be simple, fast, and tailored to detect the problems which typically occur with the process. Thus, experience is needed with the process, before it can be determined what type of monitor is needed. The other is off-line, process-improvement characterization. For this, a very wide variety of tools---everything in the material scientist's bag of tricks---is used. This would include x-ray (theta-two theta scans, phi-scans, pole figures) and electron diffraction for crystalline texture (e.g., RHEED), microscope synchrotron x-ray diffraction, RBS, Auger profiling, scanning probe microscopes (STM,AFM, ...), SEM, TEM, optical microscopy, film thickness and magneto-optical flux imaging. For complete characterization it is necessary to have T_c, I_c, J_c, inductive magnetic measurements (ac and SQUID), and J_c measurements as a function of strain and applied magnetic field. Important for the magnet designer is how J_c depends on <u>both</u> field strength and orientation. In most cases J_c is strongly dependent on field angle, and futhermore, the details of the dependence vary from sample to sample.

An understanding of how current flow is related to microstructure is essential for improving the current carrying capacity of coated HTS tapes. Magneto-optical flux imaging is used to study superconductors in the presence of magnetic fields. The applied field induces superconducting shielding currents which flow in closed loops and are concentrated in regions of strong flux pinning. Thus, images identified in this way directly identify regions of high/low intragranular current density. The nature of transport current flow is largely determined by the intergranular current density, that is, the connectivity between superconducting grains. A grain with high intragranular current density will carry no transport current if it is poorly coupled to the neighboring grains. The transport current path is a result of a percolation process among the superconducting grains and can be determined quantitatively by imaging its magnetic pattern. Combined with an electron microscope image, the method relates variations in current density to aspects of microstructure and can be exploited for mapping the path of the current through the polycrystalline array in HTS coatings. The images directly show the barriers to current flow revealing both the influence of cracks and of the dislocations that form in low angle grain boundaries. The importance of measuring the crystalline misalignment angle stems from the fact that J_c decreases as the misalignment angle increases. In results to date for YBCO, coatings applied up to 3μm film thickness, increases in film thickness result in exponentially decreasing J_c.

Commercialization requires diagnostic techniques that can be developed into useful on-line diagnostic tools for use in quality control. Non-contact optical techniques using the highly developed instrumentation of the optical industry promise both rapid real time measurements useful for control as well as quick instrument development with off the shelf components. Several optical techniques based on light scattering would appear to be immediately applicable to both research and process control needs by assessing grain orientation, chemical composition, and surface morphology. These techniques, Raman spectroscopy, ellipsometry, and light scattering/surface imaging could in principle be applied to all layers composing a coated conductor (i.e. substrates, buffers, superconductor, encapsulating) though details and exact methodologies (wavelengths, incident power, etc.) can not be determined until the coated conductor manufacturing technique is finalized.

Raman spectroscopy has the capability of measuring the local crystal orientation. The technique is based on the dependence of the Raman scattering amplitude of incident polarized radiation on the relative orientation of crystal lattice and the incident radiation. Normally the incident radiation is

provided by a laser (such as an Ar+) and thus crystal orientation is determined over the spatial region illuminated which can be made very small ($\sim.25$ μm^2 surface area for an Ar+ source with depths on the order of 1μm) or allowed to cover large areas for rapid surveys subject to instrumentation limits (i.e. optics and irradiation power). Measurement of the Raman scattering intensity for a series of different incident polarizations allows complete specification of the crystal orientation[9]. Thus the absolute in-plane orientation, intragranular orientation, and c- axis tipping can all be measured. Furthermore, the degree of in-plane correlation between granules could be assessed quickly over large regions by using appropriate imaging optics and illumination regions.

Ellipsometry measures the change in the polarization characteristics of light reflected from a surface as functions of wavelength, polarization direction, incidence angles, etc. Basic ellipsometers are relatively simple devices employing a source of radiation (possibly monochromatic), polarizer section (linear polarizer and linear retarder), sample and holder, linear analyzer, and detector. Automated and spectroscopic ellipsometers are more complex requiring control systems and motor driven optical components as well as a monochromator/spectrometer but have the advantage of making very rapid measurements.

The intensity of the light reflected from the sample being analyzed by an ellipsometer is dependent on the angular orientation of the surface with respect to the incident polarized light, the light's wavelength, and the dielectric tensor of the material. Thus ellipsometry gives insights into both surface structure (via orientation) and chemical composition (dielectric tensor). The dependence on the chemical composition allows ellipsometry to be employed in studies of the spatial and temporal variation of the chemical makeup of the surface. Pseudodielectric functions derived from ellipsometric measurements could be used to identify chemical compounds and the oxygen content of HTS layers[10]. Also, since the dielectric tensor is dependent on the physical state, it should be possible to use ellipsometry to identify different phases of materials.

Ellipsometry instrumentation is simple, rugged, easily automated and thus suitable for on-line measurements needed for quality control functions. With its overall capabilities it provides a valuable research complement to x-ray diagnostics and has the potential of being an excellent on-line processing diagnostic.

Simple light scattering/imaging techniques should be usable to provide continuous on-line detection of defects in substrates and over layers of coated conductors. Such real time continuous monitoring is seen as crucial to scaling production processes up to commercial levels. Currently, long lengths of HTS wires (BSCCO) do not have the same performance as short lengths for reasons assumed to be related to variations in properties along the wire length. By detecting the variations during manufacture, several possibilities become viable. The process can be modified in real time eliminating or reducing the observed defect, defective areas can be identified and then removed in a post production phase, and the process may become well enough understood to reduce or eliminate defect generation. Gross defects such as breaks, gaps, excessive roughness in layers should be detectable and quantifiable with simple light scattering techniques (i.e. amount of light reflected by the surface specularly for breaks and diffusely for roughness) while very small scale imperfections if important may require more precise imaging type measurements (i.e. Foucault) coupled with digital image processing. Studies necessary

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to ascertain the types, numbers, and sizes of defects that are important will be necessary before definitive answers on techniques are made.

Research on diagnostic instrumentation and techniques must be conducted to develop measurements required both to support the research and development phase of coated conductor technology and also to supply the needed process control equipment for full scale commercial manufacture. Unfortunately, the complete research needs cannot be specified until details of the coated conductors and manufacturing process become finalized. It is expected that fundamental approaches to the necessary measurements will be available but significant research will be required for adapting and refining chosen techniques to the specific requirements of the HTS industry.

However, some research requirements that are both pertinent and generic to the general needs of coated conductors and their manufacture can easily be identified. In general, this research falls into the area of characterization of coated conductor layers and the relationships between layer parameters and conductor performance. It may be possible to accurately assess the quality and character of a layer using measurement techniques described earlier. However, without a thorough understanding of the dependence of operational parameters (T_c, J_c, H_c, etc.) on the layer properties, such measurements are useless for process control and manufacturing needs. Thus a successful effort in developing the relationships will be indispensable to the deployment of effective process monitoring techniques. For the purpose of this plan, it can be considered that information to be obtained falls into the two broad areas of global and localized (or defect) parameter variation. While the division between these areas is not always clear, global variations deal with the deviation of a parameter on average (i.e. the desired layer thickness is 1 μm but the manufactured layer is actually 0.9μm) while localized variations represent deviations from the mean. (Clearly, the averaging interval affects the division between the two areas.) Global properties can be considered to be generally controllable while localized changes or defects may only be detectable. The following are areas where research must be conducted to elucidate the relationships between conductor performance and these layer parameters. The first two are global in nature while the remainder fall in the local category.

Layer Composition

Chemical layer composition will need to be monitored during manufacture though the extent and point of monitoring will be highly dependent upon the layer and manufacturing processes chosen. For certain layers (i.e. a nickel substrate) use of raw materials of known character may obviate the need for online monitoring once sufficient research has been done to allow specifications for the raw materials to be determined. As a further example in a process such as sol-gel, monitoring of the chemical composition of the sol-gel may be sufficient to guarantee high quality conductors.

Layer Morphology

The physical changes in the layer structure such as thickness, crystalline state, grain size and alignment clearly affect the final conductor and thus may need monitoring which again will be dependent upon both the layer composition and the manufacturing process. Other properties such as surface roughness may effect conductor properties and thus will need to be identified and understood.

Defect Types

Before methods can be developed to monitor for defects, the types must be identified. Expected defects would include physical changes (dimensions, physical state, inclusions, grain size, etc.) and chemical changes (stoichiometry, impurities, etc.). Such changes might exhibit themselves as cracks or gaps in a layer, causing reductions in J_e or regions without superconducting properties also reducing J_e.

Defect Size

In general, a particular defect will affect performance to an extent related to its physical size. Research must be conducted to determine acceptable sizes (length, width, depth, orientation) for all the defect types identified. Once size parameters are determined, appropriate measurement technologies can be identified for making the needed measurements. Defect number or density collections of defects either of same type or mixtures may not combine to produce cumulative effects in a straightforward manner. Some defects can be expected to be area dependent while others just surface phenomena. The overall effect of a group of defects may be greater or less than a single defect of equivalent size. In some cases, the total number of defects of a certain type along the entire length of the conductor may be important whereas other defects may add together only when occurring locally. Thus research will be necessary to determine allowable defect numbers or densities if defects are found to be sufficiently common to be acting collectively.

SUMMARY OF REQUIRED TECHNICAL R&D STEPS

This list describes a summary of R&D tasks to achieve the planned outcome of this plan.

1. General Principles of Collaboration:

The objective of the second-generation wire program is to extend existing coated-conductor technology to very long lengths (> 1 km) while still preserving high J_c values. The program plan demands the achievement of five simultaneous objectives: long length, high critical current density, high engineering current density, operation in high magnetic fields and low manufacturing cost.

Diagnostic measurements and controlled feedback are essential to any cost-effective manufacturing process. Accordingly, this plan envisions a series of studies in the laboratory which are explicitly aimed at discovering suitable diagnostic measurements. Subsequently, we envision partnerships (CRADAs) between industry and national laboratories to create a series of on-line measurement techniques.

2. Experimental studies needed to resolve certain crucial technical questions:

Maximizing the useful film thickness is a key goal. So far we have presumed that if the substrate and buffer layers have good grain alignment, the YBCO layer will do so as well. For long conductors, that point is not yet proven, and needs experimental verification.

The YBCO conductors need to be 5 or 10 μm thick, which introduces a new issue: As the YBCO layer thickens, will new mis-oriented grains form?

The variation of J_e with film thickness needs to be experimentally investigated in this program.

Developing the limits of various deposition technologies is an important part of this program plan.

Assuming a very thin passivation layer of a μm or two, the substrate can only be about 8 times thicker than the YBCO layer. Thinner substrates must be developed.

The *uniformity* of cross-section of both the buffer and the YBCO layer must be maintained to within some tolerance over the full length of conductor. That tolerance must be determined.

Experimental determination is needed of how the critical current $J_c(H,T)$ will behave when finite magnetic fields are applied to the combined coated conductor/substrate assembly.

AC losses of the actual engineered conductor must be measured early in the program. We recommend that a sub-program of AC-loss measurements be carried out, using whatever length samples are available. The AC-loss measurement experiments should be accompanied by a series of design calculations to figure out what amount of losses are acceptable in various applications.

Strain-tolerance of the entire conductor (substrate + YBCO coating) must be measured, for bending in all possible directions, including measurements of stretching or buckling of the film as the substrate changes shape.

As soon as moderately-long coated-conductor samples (> 20 cm) are available, investigations should begin to determine the thermal expansion properties of the assembly.

3. Manufacturing Process Steps:

A key question is whether long lengths can be manufactured economically. In order to ultimately achieve a cost-effective manufacturing process, several preliminary achievements are required. These include:

(1) Prepare HTS films thicker than 1 μm, with J_c above 10,000 A/mm^2 (77 K, 0 T), on single crystal substrates. This figure corresponds to I_c greater than 100 A/cm of tape width. (The long term goal is to reach 100 A/cm of tape width at liquid nitrogen temperatures and 5 T, which may be achieved with thicker films and/or further improvements in J_c.)

(2) Demonstrate similar quality films on metal substrates, using suitable buffer layers.

(3) Determine the maximum specific film deposition rate (μm per minute) which can be achieved. Identify and eliminate the defects which limit high rate growth.

(4) Determine the process window for various parameters (substrate temperature, working pressure, deposition rate, etc.) which will still permit high quality film growth.

(5) Proceed to continuous processing of short tape samples (less than one meter in length). Experiment with progressively thinner substrate tapes, and determine appropriate film and substrate thickness.

Automation is an essential characteristic of cost-effective manufacturing. Therefore one goal is to achieve an automated technology producing thousands of kilometers annually.

Reaching the program's cost goals requires process improvement, process modifications, and process substitutions. Manufacturing of coated conductors requires that high-quality films be deposited on substrates at high rates. The film deposition steps, via both IBAD and RABiTS substrate preparation, are presently too slow.

Since the thinnest commercial metal tape substrates (e.g., of oxidation-resistant nickel superalloys) are about 1 mil (25 μm) in thickness, it is important to obtain a thick superconducting film. The superconducting layer must be relatively "thick", in the range of 1 to 10 μm; whereas buffer layers, diffusion barriers, passivation layers, etc., can be thinner.

Specific numerical goals for acceptable splices should be established and incorporated into the collection of milestones.

4. Managerial Decision Points:

After 1997, it should be possible to eliminate or scale back support of any HTS film-deposition techniques which cannot produce $J_c > 5,000$ A/mm^2 (at 77 K and 0 T) on single crystals.