THE COMPETITIVE POTENTIAL OF HIGH-TEMPERATURE SUPERCONDUCTORS FOR POWER TRANSMISSION

by

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ABSTRACT

High temperature superconductors were discovered in 1987. World-wide, many groups are presently engaged in the research and development of these materials for power transmission cable applications. This thesis examines the competitive potential, on a cost-performance basis, of high-temperature superconductors as compared to conventional transmission lines. Toward this end, a broad survey of the literature on high-temperature superconducting (HTS) cables and tapes was performed. An analysis of the critical interdependencies between HTS technology and their cost-competitiveness for power transmission are presented.

This thesis makes clear that there are technical characteristics unique to HTS which place them at a significant economic handicap for alternating-current power transmission as compared to direct-current power transmission.

HTS tape is the integral component of a HTS cable. In turn, silver metal is an integral component of HTS tapes and there is little technological scope for reducing the amount of silver required for HTS tape. While the cost of silver was found to be a minority fraction of the total cost of HTS tape, this cost alone, on a cost performance basis, would approach the entire final installation cost of a standard overhead direct-current transmission line for a 1 km length. However, because the properties of HTS tape continuously deteriorate with distance, their competitiveness would also progressively deteriorate for longer transmission distance.

The reduction of transmission losses is not a compelling source of competitive advantage for HTS cable. A HTS direct-current cable would not eliminate all transmission losses and there is considerable technical debate over whether such a cable would have any loss-savings advantage over a standard direct-current transmission line. However, were a completely loss-free transmission line possible, it would merit a premium, under the most optimistic scenario, of approximately 76% over the final installation cost of a standard direct-current overhead transmission line, and about 7.6% more than the cost of an equivalent underground direct-current cable.

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Acknowledgements

Regarding my thesis I'd like to thank my advisors Prof. Robert Rose and Dr. Bruce Strauss. They allowed me unprecedented autonomy to conduct my analysis. I received no funding for producing this thesis and have no personal stake in the topic. The idea for the project first came from Dr. Paul Levy when I approached him regarding something entirely unrelated. I am also grateful to John Howe of American Superconductor for his direction and insight into direct-current power transmission, also a new field for me. I chose to pursue the topic for the purely pragmatic reason that it struck me as ideally suited to simultaneously satisfy the rigorous thesis requirements for the MSc. degrees in Materials Engineering and in Technology and Policy here at MIT.

I am indebted to the many researchers in the high-temperature superconductivity community for building the edifice of knowledge on which this thesis is based. Unfortunately I have not here contributed any "new" knowledge to the field, least-of-all to those in the high-temperature superconductivity community. The value of this thesis lay in its synthesis, in the *reasonableness* of its arguments, and in its ability to connect the seemingly disparate facets of HTS technology to their economic relevance.

Pertaining to my academic career at MIT, I'd like to thank Prof. Richard de Neufville of the Technology and Policy Program for first admitting me to MIT. I'd also like to thank Prof. Sadoway, Dr. Floyd Tuler and the Alcan Aluminum Corporation, and H & K.

I'd like to convey my appreciation to the many good people I've crossed at MIT. bc for his "kick-ass" sense of humor and lengthy technical assistance. To C^3: cute, charming and considerate. To ay, jh, zy, and to ap, cb, eb, fa, jv, jl, jc, us - riotous blokes all.

"Through indirections find directions out."

-Shakespeare, Hamlet

"To be sure: among scholars who are really scientific men....you may really find something like a drive for knowledge, some small, independent clockwork that, once well wound, works on vigorously *without* any essential participation from all the other drives of the scholar. The real "interests" of the scholar therefore lie usually somewhere else - say, in his family, or in making money, or in politics. Indeed, it is almost a matter of complete indifference whether his little machine is placed at this or that spot in science, and whether the "promising" young worker turns himself into a good philologist or an expert on fungi or a chemist: it does not *characterize* him that he becomes this or that."

-Friedrich Nietzsche, Beyond Good and Evil (6)

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Chapter 1
Introduction

1.1 Impact of the Discovery of High-Temperature Superconductors

In 1987 there was a tremendous increase in scientific research on high temperature superconductors. Figure 1 shows that almost overnight the HTS publication rate doubled that of the long-established LTS field. However, the HTS publication rate has proved incapable of sustaining, let alone increasing from its initial publication rate. Also surprising is that this massive growth in work on HTS has not been at the expense of LTS research. LTS research has continued to grow at nearly *precisely* its rate prior to the discover of HTS. Two reasons for this become apparent. Firstly, the foundation for interest in LTS is based on research programs, funding patterns, and a network of relationships between national laboratories, industry and university developed over decades. Secondly:

" ...HTS materials have so far not attacked the markets of LTS at all. Rather they have expanded the domain of superconductivity into new fields where the refrigeration complexities or costs of LTS materials make superconductivity economically unattractive." [1]

The foundation for research in HTS was based on scientific curiosity, on the hope for quick progress into fantastic new applications, and on the fear of losing out on potentially the greatest technological breakthrough of the century to other scientists and to other countries.

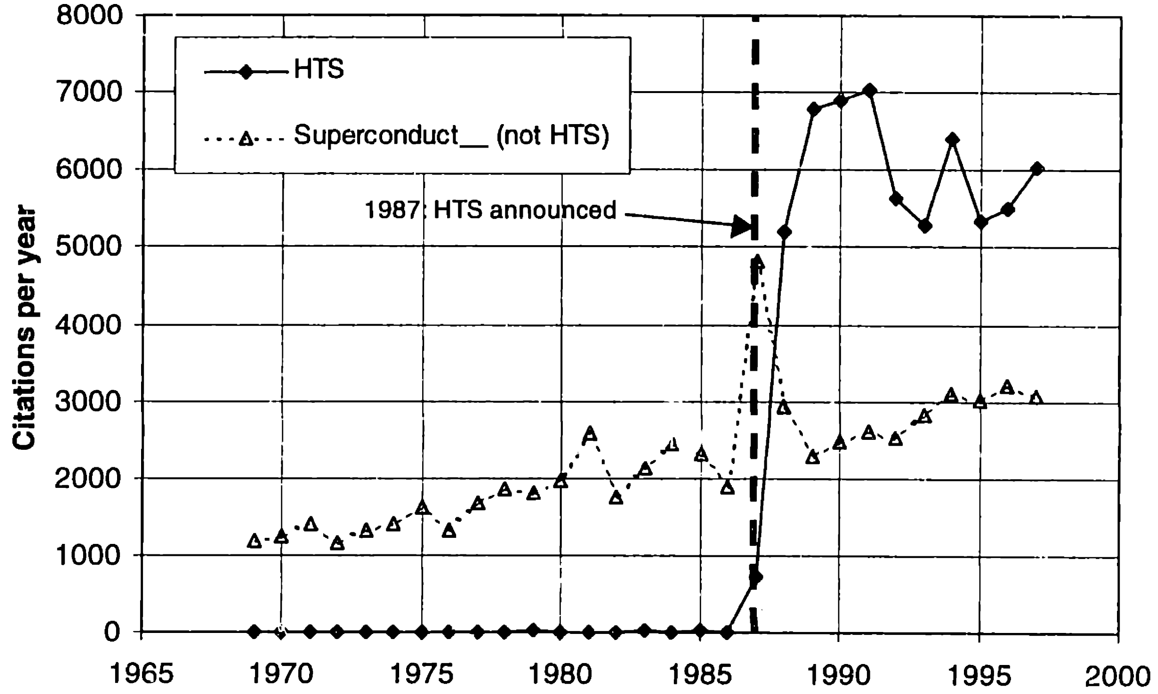


Fig. 1: Trends in Superconductivity Research

Results from INSPEC search

1.2 Advantage of Liquid Nitrogen

Scientific curiosity aside, there was a very pragmatic reason for interest in the new materials. Superconductivity could now be easily attained through liquid N_2 at a temperature of 77 K compared to the 4.2 K of liquid He. Liquid N_2 is much cheaper at about 2% the cost of liquid He [2]. Liquid N_2 possesses more advantageous properties from a practical engineering point of view – higher latent heat of vaporisation, higher thermal conductivity, heat transport without film boiling, and a higher dielectric strength of 2 MV/m compared to 1.4 MV/m for liquid He. The following advantages are tabulated:

a) better thermal stability of the system
b) lower investment costs for cryogenic systems
c) decreasing operating costs for cooling because of the greater cooling efficiency from operating at higher temperatures.
d) Liquefied nitrogen cooling starts from an existing infrastructure based on known technology [2].

HTS therefore held out the promise of a less complicated, more reliable, more economic design of superconductivity applications.

1.3 Cables

In order for a HTS material to realize the superconducting state, an operating-parameter window must be met. The crucial parameters are temperature, applied current density and externally-applied magnetic field. In terms of these operating parameters, transmission cable is one of the least demanding applications for HTS materials because no externally-applied magnetic field would be intended. The HTS cable would only be subject to its own "self" magnetic field set up by the current it carries.

HTS cable is not envisioned for use in overhead power lines because of the threat of lightning strikes and the exposure of the HTS cable to mechanical vibration and to the vagaries of the weather [2]. For now the only serious consideration is for cable - either buried underground or in urban underground conduits.

Figure 2 shows the slow rise in research interest in HTS cables since 1987. However, fig. 2 does not break down the interest by application. The parallel exponential growth in research on "non-HTS" cables begs the possibility that LTS & HTS conductors compete, or overlap for certain cable applications. To answer this, the abstracts of all 113 SC cable citations from 1997 were examined and the results tabulated in broad groupings in table1.

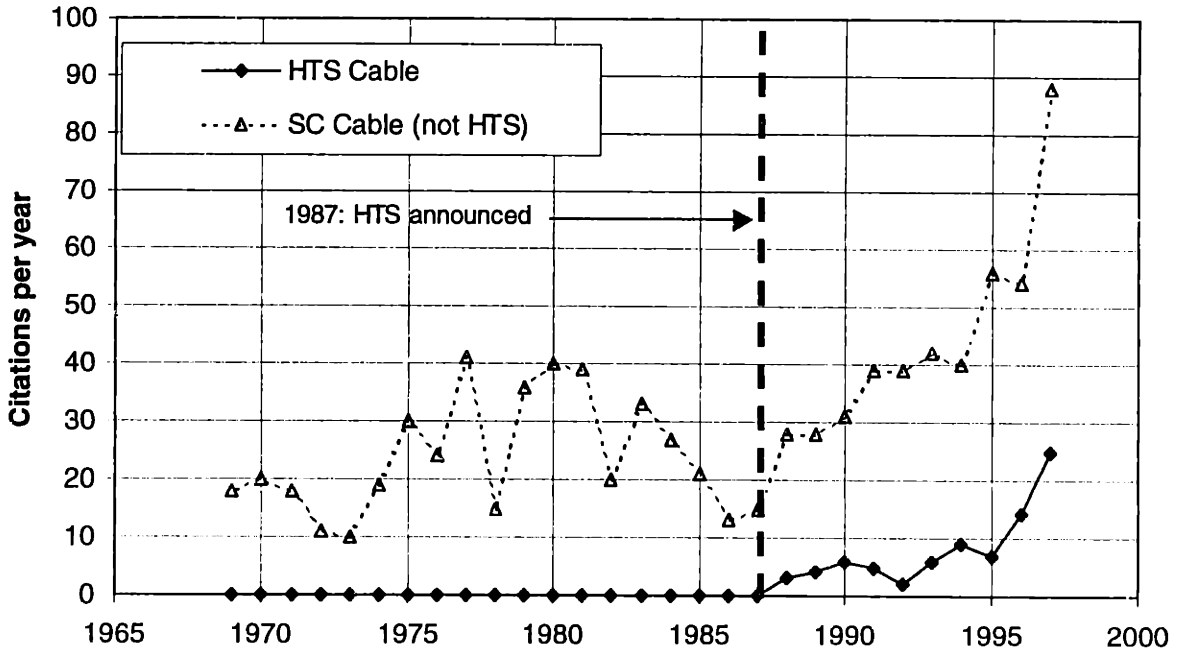


Fig. 2:Trends in Superconducting Cable Research

Results from INSPEC search

Table 1 makes clear that interest in HTS cable technology is exclusively confined toward power transmission applications. Even more compelling is the apparent complete lack of interest in LTS cables for power transmission. 100% of the HTS cable papers pertained to their use as transmission cable, and 0% of the LTS cable papers related to transmission line application. Nonetheless, there is one project underway by the Korea Electrotechnology Research Institute to develop a LTS prototype transmission cable, which perhaps did not publish in 1997.

Table 1 - Breakdown of the 113 "Superconducting Cables" Papers in 1997

Application	HTS	Either relevant to both HTS & LTS, or no clear division.	LTS
Transmission Lines	**25**	**4**	**0**
Generators	0	0	3
SMES	0	0	20
Cable – miscellaneous	0	20	26
High-Energy-Physics Applications	0	0	15
Total	25	24	64

To provide a snapshot-in-time of ongoing work on HTS cables, Table 2 describes the 29 HTS cable papers from 1997 in terms of country of origin, organization and central theme. Note that it is common for the same underlying development to become the source for multiple papers. There are many groups in many different countries developing HTS cables in parallel.

Table 2 Snapshot of Research into HTS Cables in 1997

Country	Organization/s	Central Theme of the Publication
Denmark	Dept. of Electr. Power Eng, Tech Univ., Lyngby	Three 1-m long cable prototypes of different designs
	Res. Inst. Of Danish Elect. Utilities, Lyngby	Study of 450 MVA, 132 kV cable.
Russia	Dept. of SC Wire & Cable, JSC VNIIKP Moscow	Theoretical analysis of current distribution in the cable.
Germany	Siemens AG, Erlangen	10-m prototype cable
	Ibid	Ibid
Italy	Pirelli, Milan	Machine-stranded 50-m prototype cable. (same cable as Pirelli/American Superconductor effort in the US.)
	Pirelli, Milan	Concepts and motivation for adoption into grid.
	Dipt. Di Ingegneria Electtrica, Naples Univ.	System diagnostics for incorporation into grid.
UK	BICC Cables, Wrexham	Long-length properties of Bi-2223 tapes for HTSC cable.
USA	Southwire Co, Carrollton, GA (construction) + Oakridge National Labs (testing). + Intermagnetics General Corp.(provides Bi-2223 tapes)	Two 500 A & one 2000 A prototype cables.
	Ibid	Ibid
	American Supercond. Corp, Westborough MA (Bi-2223 tapes) + Pirelli Cable + Electric Power Research Institute	50-m cable prototype.
	Ibid	Ibid
	Los Alamos Nat. Labs	Describe calorimeter for measuring AC losses in HTS cables.
Japan	Furukawa Electric Co., Chiba	66 kV, 2 A, 5 m prototype cable & manufacture of a 50 m prototype.
	Ibid	Ibid
	Ibid	Ibid
	Sumitomo Electr. Ind., Osaka	Machine-stranded 66 kV class, 50 m prototype and its suitability for retrofit into existing ducts.
	Ibid	Ibid
	Ibid	Ibid
	Ibid	Development of current leads for HTSC transmission cables.
	Power Eng R&D Center, Tokyo Electric Power Co., Yokohama	5 to 7 m cable prototypes & 50 m prototype.
	Ibid	Ibid
	Ibid	Alternate means of calculating HTS cable self-field losses.
	Dept. of Elect. Eng, Tsuruoka Nat. Coll. of Tech., Yamagata	AC losses in cables.
	Chubu Electric Power Co, Nagoya	Created current lead for 77 kV-class HTSC cable
	Aichi Inst. Technol.	Transient stability of power system for SC transmission.
	Electrotech Lab, Ibaraki	Potential for HTS cable in power grid.
Korea	Korean Inst. Electr. Eng.	Optimal installation of SC cable in urban area.

1.4 Current Density Advantage

The vast majority of power transmission occurs under alternating current (AC) conditions. It is therefore not surprising that nearly all the present interest in HTS cables is directed with AC operation in mind. The most concerted effort in the world to apply HTS AC cable is in Japan where development efforts are almost exclusively focused on exploiting the clearest advantage of HTS conductors, which is their 10 to 100-fold greater current density capability over normal conductors. Far greater current may be transported within the same space. The intent is to harness this advantage by retrofitting HTS AC cables into conduits presently used by under-ground copper lines in densely populated urban areas such as Tokyo. This allows transmission capacity to be increased without the expense of carving new power transmission right-of-way through an already-congested maze of underground public works. If the HTS cables achieved sufficiently high current-carrying capacity then the cost of intermediary transformer substations might be eliminated by transmitting the power at lower voltage and higher current. One goal is to produce a 66 kV/1GVA cable by 2010.

In October 1998, a project was announced in the US to retrofit a 122m stretch of nine 4-inch-diameter copper cables in downtown Detroit using 3 HTS cables each carrying 2400 A at 2.4 kV. The project is forecast to cost $5.5 M, with the Department of Energy funding half of the cost under an urban redevelopment project. The cost performance measure for the project is therefore $6261/kAm.

1.5 Materials Classes

In 1988 there were three main classes of HTS: YBCO, BSCCO and TlBCCO. YBCO had been the most thoroughly studied up to that time.

Table 3: The Transition Temperature of the Common HTS Materials

Stoichiometric Formula	Shortform name	Superconducting Transition Temperature (degrees kelvin)
$BiSr_2Cu_1O_x$	Bi-2201	7
$Bi_2Sr_2CaCu2O_x$	Bi-2212	92 [3]
$(Bi,Pb)_2Sr_2Ca_2Cu_3O_x$	Bi-2223	108 [3]
$YBa_2Cu_3O_x$	Y-123 orYBCO	95
$HgBa_2Ca_2Cu_3O_x$	Hg-1223	135 [4]
$TlSr_2Ca_2Cu_3O_x$	Tl-1223	125

1.5.1 BSCCO Materials

Nearly all applications of HTS foreseen at liquid nitrogen-range temperatures envision using Bi-2223. Bi-2223 will therefore be analysed in depth later in chapter 2.

Aside from the higher T_c possible, the BSCCO superconductors have practical advantages to YBCO in terms of requiring a lower processing temperature, oxygen stability, and the absence of rare-earth elements [5].

1.5.2 YBCO Materials

As early as 1988 the PIT method was used to manufacture 252-filament YBCO wire. A two-stage transition into superconductivity was observed. Superconductivity commencing at T_c of 95K, and zero resistance finally only seen at 20 K [6]. This gradual transition to superconductivity has been blamed on lower-T_c phases forming by reaction with the Ag sheath, or because of impurities forming at the grain boundaries [6,7].

The oxygen stoichiometry of $YBa_2Cu_3O_x$ is of critical importance to its superconductivity. T_c is maximized for x = 7; whereas for x = 6 the material is merely a semiconductor with the oxygen atoms no longer connecting copper atoms along chains. Oxygen processing appears to require less precision for the other HTS materials [7].

Over the long term H_2O and CO_2 in the atmosphere will react with YBCO to degrade its properties, thereby requiring atmospheric protection. However, the same is true for Bi-2223. They therefore require a coating.

Some improvements to J_c may be possible through the partial substitution of Y by other rare earth elements. $Y_{.6}Er_{.4}$ for example was seen to yield a higher J_c [8].

1.5.3 Tl-1223 and Hg-1223 Materials

Some researchers believe Tl-1223 to be a promising alternative to BSCCO and YBCO for high-current applications at 77 K because of their ability to maintain high J_c in the presence of external magnetic fields; they have a high irreversibility line. Poor inter-CuO layer coupling in BSCCO is blamed for reducing J_c in the presence of magnetic fields [9]. Tl-1223 & Hg-1223 each separate Cu-O layers with only a single Tl-O, or Hg-O layer respectively, thereby improving coupling, and hence their current carrying ability within a magnetic field.

Less attention has been paid to the mercury (Hg) system, in part because of the chemical instability of Hg-bearing compounds. However, stability is said to be "greatly improved" with the partial substitution of Hg by Tl or through the addition of small amounts of rare-earth oxides (ReO_2) [9]. Unfortunately, Hg 1223 tapes are also more complex to produce and the reproducibility of tape properties via current processes is too poor to be commercially viable [4].

The toxicity of both Tl and Hg is considered an important potential barrier to the serious consideration of these classes of HTS for widespread application [10].

From a production viewpoint, Tl-1223 films are still in the exploratory phase of research with different processing routes competing for pre-eminence. The powder-in-tube route has failed to producing Tl-1223 with high J_c in magnetic fields due to lack of grain alignment. A number of other deposition processes have been examined: electrodeposition, electro-phoretic deposition, dip coating, and finally, spray pyrolysis being the most common. J_c of 2000-4000 A/cm^2 at 77 K have been realized thus far.

While Tl-1223 tape is said to have the greatest potential for a HTS magnet operating at liquid nitrogen temperatures, it suffers from the "weak-link" defect discussed in greater detail in section 2.3.2[11].

Hg-1223 has the highest T_c of any HTS reported.

Chapter 2
HTS Tapes

HTS tapes are the fundamental building block of HTS cables.

2.1 Current Density

2.1.1 Basic Knowledge

The critical current density (J_c) is the most fundamental measure of the performance of a HTS - or any superconductor. It depends on the maximum current the HTS is capable of transporting while still remaining in the superconducting state. This current is known as the critical current - I_c. Dividing I_c by the HTS oxide cross sectional area gives J_c. The fill factor is the fraction of the cross-sectional area of the tape comprised of actual HTS oxide material. J_{eng}, is the average current density of the tape over the whole tape cross section:

(eqn. 2.1.1-1) $J_c = \frac{I_c}{A_{hts}}$; (eqn.2.1.1-2) $f.f. = \frac{A_{hts}}{A_{tape}}$; (eqn.2.1.1-3) $J_{eng} = f.f.J_c$

2.1.2 Reporting the Current Density

"(Ag/BSSCO) .. *tapes are not perfectly superconducting.* (They) *have broad resistive transitions with current...* (which) *can be described as a power law relating resistivity, ρ, to current density J:*

(eqn.2.1.2-1) $\rho=kJ^n$

where k, the constant of proportionality, and n, the exponent are constants characteristic of the superconductor. I call (such) *materials power-law cryoconductors.*" [12]

The I-V curve of figure 3 demonstrates the gradual transition from the superconducting state to that of a normal conductor. The HTS community therefore relies on a convention to provide for meaningful comparisons of J_c results from different researchers. The most widespread convention is to base J_c on the current which flows through the superconductor under a potential difference of 1 μV/cm.

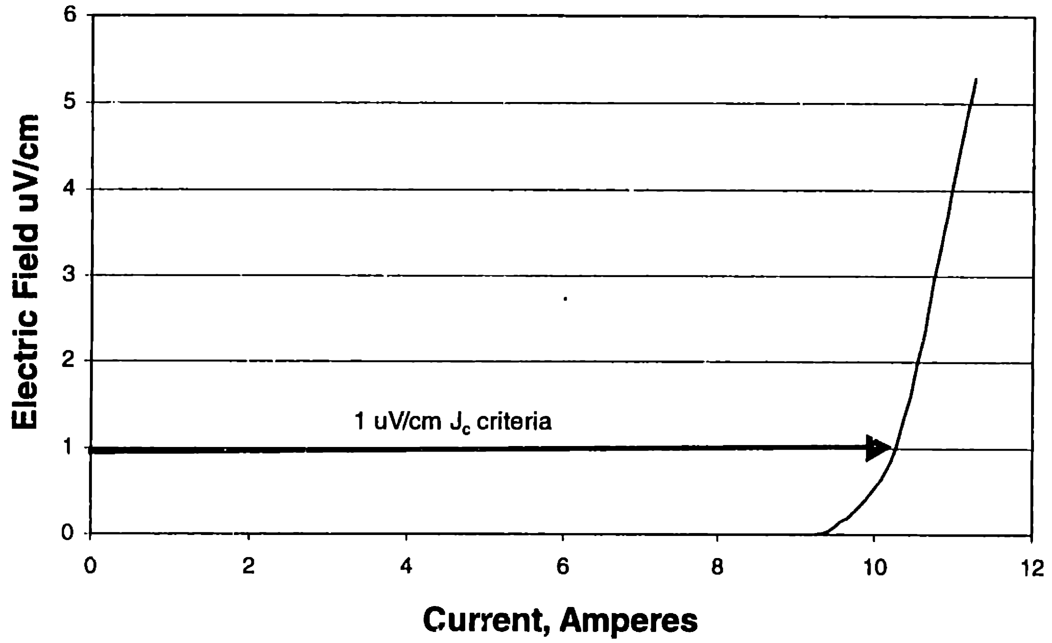


Fig 3: The I-V curve of a Bi-2223 OPIT tape

ref. 13

A less-common convention, most often used by Japanese researchers, is to report J_c based on the current which yields a resistivity of 10^{-13} Ω-m. A resistivity-based convention is the standard means by-which the low-temperature superconductivity community measures J_c. For $J_c < 100$ kA/cm^2, the 10^{-13} Ω-m criteria will slightly understate J_c as compared to the 1 μV/cm criteria. Above 100 kA/cm^2 this method will slightly overstate J_c. To-date, no HTS tapes possess $J_c > 100$ kA/cm^2, so the 10^{-13} Ω-m is presently a more conservative estimate of J_c than the 1 μV/cm criteria.

A potential difference of 1 μV/cm, while low, still implies some resistance loss, depending on the current level, which may or may not be acceptable for cable applications. A 2000 A HTS cable operating at I_c would have a resistance loss of 0.2 W/m for example. The maximum operating current might therefore need to be based on J_c slightly lower than that given by the 1 μV/cm criteria.

For power transmission cable applications we here assume operation at the liquid nitrogen temperature of 77K, and with zero externally-applied magnetic field. Intended to provide only the most general of overviews, table 4 presents a series of reported values of J_c. Whether tapes of these properties may be manufactured for use in cables is a different issue. This data also say nothing about the fill factor, which is a crucial property.

The J_c of single crystal forms of Bi-2223 is a practical "rule-of-thumb" guide to an upper limit on J_c because it is a kind of "best-case" scenario - current flow in HTS tape will always need to traverse multiple grains, and therefore never be as perfect as a single crystal.

TABLE 4 - Frame of Reference Reported Current Density		
Year of Measurement		J_c kA/cm^2 (1 µV/cm criterion; 77 K, 0 T)
1998	Bi-2223 single-crystal thin film	1000 [14]
1995	Bi-2223 tape – the 10 µm layer next to the Ag-sheath.	110 [15]
1995	Bi-2223 tape – the 2-3 µm layer next to the Ag sheath	80 [16]
1998	Bi-2223 filament – taken from a 58 kA/cm^2 sample.	80 [14]
1998	Bi-2223 tape	54 [14]
1998	Bi-2223, 19 filament, short length (10 cm), OPIT	73.8 [17]
1997	Hg-1223 on Ni substrate; controlled vapour/solid reaction technique	25 [4]
1997	Bi-2223 Electrophoretic deposition.	30 [18]
1997	Bi-2223 short tape, OPIT process; called: "a record-to-date J_c"	58 [19]
1997	Bi-2223 , 10 m, 27 filament tape; OPIT	10 [20]
1997	Tl-1223/Ag tape 50-m length	60 [21]
1997	$Hg_{.8}$ $Tl_{.2}Ba_2Ca_2Cu_3O_x$ via doctor-blade casting/vapour reaction technique.	22 [9]
1995	Bi-2223, short-sample, OPIT; mono-filament	50 [22]
1995	Bi-2223, short-sample, OPIT; 19-filament, rolled	30.7 [22]
1995	Bi-2223, short-sample, OPIT; 19-filament, pressing	36.5 [22]
1995	Bi-2223, short-sample, OPIT; 85-filament, rolled	39.7 [22]
1995	Bi-2223, short-sample, OPIT; 85-fillament, pressed	45.5 [22]
1995	Bi-2223 361-filament Metallic precursor process, 10 m sample.	22.4 [23]
1993	Bi-2223 tape produced with accordian folding technique	8.8 [24]
1993	Bi-2223 259-filament tape; 0.03 m long Best –reported to-date for high-filament tape.	17.7 [3]
1993	Bi-2223 259-filament tape; 8m long Best –reported to-date for high-filament tape	8 [3]
1993	Bi-2223, multifilament, MP processed short tape	17.7 [25]
1992	Bi-2223 single-core wires	69 [as cited in 3]
1992	Bi-2223 short tape	8 [13]
1991	YBCO short tape	2 [8]
1988	YBCO polycrystaline	7.4 [10]
1988	YBCO extruded wire	.06 – 0.65 [10]
1987	YBCO high-quality thin film	100 [10]

2.2 Manufacturing

It was prophetically written in 1988:

"The eventual use of the new superconductors may require new processing techniques as innovative as the discovery of the materials themselves." [7]

Ten years later Bi-2223 is the most promising class of HTS for large-scale applications precisely because of its suitability for processing. All experimental and prototype HTS cables to-date have utilized the Bi-2223 tape conductors [26]. No other tape manufacturing technique has proceeded even remotely so far down the path toward commercialization. **It is therefore impossible to imagine the near-term - say 5 to 10 year - adoption of HTS transmission cable if Bi-2223 tapes based on current oxide powder-in-tube process proves unsuitable.**

2.2.1 The Oxide-Powder-in-Tube Process

The most widely utilized manufacturing route for Bi-2223 conductors is the oxide powder-in-tube (OPIT) process. It has been used to produce kilometer length tapes and appears scalable for mass production. The generic steps are as follows:

a) **Powder/Precursor Preparation.** An oxide powder having the same chemical stoichiometry as the final superconducting material is manufactured. Powder quality is of vital importance to the final properties of the HTS tape. Many processing routes exist for manufacturing the precursor, which is an involved process in its own right. Solid-state reaction, co-precipitation, sol-gel, and the freeze-drying method are the main ones. Freeze-drying yields the highest-quality powders [27]. This is a critical step, and the final properities of the tape are critically dependent upon it.

b) **Powder Packing** The powder is packed and sintered into a tube shape. A hollow Ag tube (former) is filled with the sintered powder.

c) **Drawing.** The tube is drawn through a die into a smaller cross-sectional area, usually having hexagonal shape.

d) **Re-Drawing.** For multifilamentary tapes, the thin tubes produced in step (c) are cut into pieces. Courtesy of their hexagonal cross section they may then be neatly packed into bundles of 7, 19, 37, 55, 61, 81 or more tubes, placed in another Ag tube, and drawn through a die as per step (d). Steps (c) and (d) may be repeated depending on how many superconducting filaments are desired in the final tape. Limits are placed on the reduction ratio (R) of the Ag sheath. Above an R of approximately 20, cracking of the Ag may occur. This problem may be mitigated through use of intermediate annealing at higher temperatures to make the Ag malleable once again [6]. There are also limits to the number of filaments which are possible because of the onset of the sausaging defect for slender filaments.

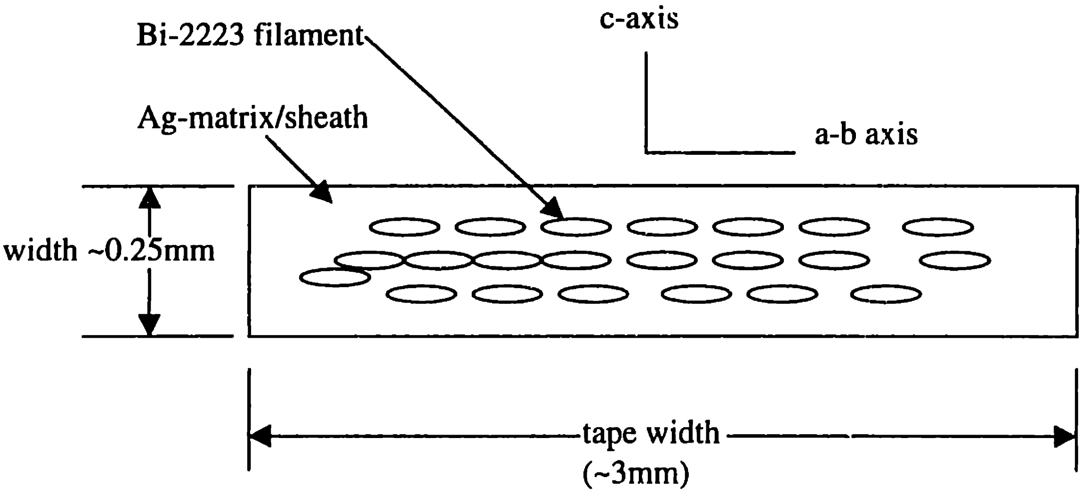
e) **Twisting <optional>** The final tube of multifilamentary HTS wires may undergo a metallurgical process to introduce a twist of a certain pitch if it is believed that this will improve the tape properties.

f) **Rolling/Pressing.** The product of step (d) - or of step (c) for mono-filamentary wire – is rolled into tape.

g) **Sintering** The tape is thermally treated – typically at around 840 C - to promote high-aspect-ratio superconducting oxide grains which have their lattice "c" directions perpendicular to the tape surface. Iterative sintering and rolling deformation may be involved to optimize properties.

The final tape is *typically* about 3 mm wide by 0.25 mm thick, with a "fill-factor" of 0.3. The fill factor is the fraction of the cross-sectional area of the tape which is Bi-2223. Figure 4 illustrates a typical schematic cross-section of a multifilamentary tape.

Figure 4: Schematic of a HTS Tape



The theoretical density of Bi-2223 is 6.1 g/cm^3, however the final density realized by Bi-2223 within the tape for the OPIT process is typically 4.5 g/cm^3, or 75% of the fully-dense oxide [28].

The OPIT process is yet young and there undoubtedly remains scope for refining and optimizing the process to yield higher-J_c tapes. For example, slow cooling after the sintering process has been credited with increasing the J_c either because of the higher tape oxygen content or because of strain relaxation it facilitates between the Ag and the oxide, which have different thermal expansion coefficients [29].

Multifilament tapes have a manufacturability advantage over high-J_c mono-filamentary tapes because the uniaxial pressing used for monofilament tapes not practical for continuous production of long-length tapes: rolling is needed [22].

2.2.2 The Crucial Role of Silver

To the author's knowledge, all processing routes for Bi-2223 tapes, and certainly all using the OPIT process, use silver encapsulation during processing. While expensive, silver is indispensable for the following reasons:

- **Permeability to oxygen.** The silver sheath is highly permeable to atomic oxygen . This is of critical importance to oxide formation in the OPIT process. For reference, at 830 C the oxygen diffusion coefficient is D= 2.42×10^{-5} cm^2/s [as cited in 30].
- **Nonreactivity** with the HTS precursor material. In fact evidence exists that Ag is the ***only*** metal satisfying the nonreactivity requirement. Platinum-group metals react with BSCCO superconductors to eliminate their superconductivity, and gold suppresses the superconducting transition termperature [5]. As an aside, Ag was also found to be the only material inert to melt production of YBCO, therefore recommending itself for use as a crucible material [7].
- **Silver-induced texturing.** The silver sheath appears to provide a site for orientating the HTS to greatly increase its J_c.

Other important functions which, while not requiring silver *per-se*, are nonetheless satisfied by using silver as the sheath:

- **Structural Support**. The HTS compounds are ceramic, and hence inherently brittle. It is therefore common to all tape manufacturing schemes (besides the OPIT process that is) that the HTS material be supported by a casing or substrate which provides enough flexibility to allow them to be handled and wound for storage.
- **High thermal conductivity** allows for rapid thermal dissipation which is important for Type II superconductors where flux-jumping can cause high local rises in the temperature of the HTS, thereby threatening the superconducting status of the tape.
- **Backup conductor.** A fundamental engineering requirement for all HTS (and LTS also) tapes is for the HTS material to be thermally and electrically connected to a substrate, or sheath, of normal conductor. In the event of either a) a break in the superconducting path, or b) the superconducting material locally quenches to above T_c in some isolated section, the current may shunt across the normal material without cutting the flow.
- **Atmospheric protection.** The sheath prevents corrosion and degradation of the HTS core from the atmosphere [27].
- **Thermal Expansion Coefficient.** Matching the sheath and HTS coefficients of thermal expansion is important to prevent the HTS from cracking during cool-down to 77 K. Ag has a mean thermal expansion coefficient of 19×10^{-6} /C, while that of the Bi-2223 is 8.1×10^{-6} /C [24]. The HTS will therefore be in compression after cooling to superconducting temperatures. While not ideal, this preferable to placing the HTS into tension since most oxide materials are stronger in compression than in tension [10].

2.2.2.1 Silver-induced Texturing

Research results show that the J_c across the Bi-2223 oxide core of tapes is non-uniform, with J_c being highest around the periphery where the oxide contacts the sheath. In fact I_c has been linearly correlated to the total length of Ag/oxide interface as measureed from a cross section of the tape [as cited in 29]. This suggests that promoting Bi-2223/Ag interface is key to improving tape J_c.

It has also been observed that across the tape width, J_c is 3-5 times higher at the edges as compared to the center. J_c of 110 kA/cm^2 has been measured for the 10 μm thick layer next to the top face of the core [30]. Such observations allude to the possibility of developing much higher tape-*average* J_c by changing the processing conditions. It is therefore valuable to understand the underlying physical mechanisms causing these inhomogeneities in tape J_c. At least for the OPIT process, the reasons are believed to center on the ability of Ag to promote formation of the Bi-2223 phase during sintering in the following manners [30]:

a) The silver sheath may prevent the evaporative loss of Pb through outdiffusion. Pb is needed for formation of Bi-2223 phase.
b) The shape of the cavity within the silver sheath promotes nucleation and growth of Bi-2223 phase with their faster-growing a-b plane parallel to the tape surface.
c) Silver induces liquid to form at sintering temperatures, which may promote Bi-2223 formation at the Ag/Bi-2223 interface.
d) The formation of Bi-2223 phase is believed to result in a release of oxygen according to the following proposed reaction:

$$\text{Bi-2212} + Ca_2PbO_4 + CuO \rightarrow \text{Bi-2223} + O_2$$

For the reaction to proceed, O_2 must diffuse away from the HTS core area. The diffusion of O_2 along the Bi-2212 a-b planes ($D=2.42\times10^{-5}$ cm^2/s at 830 C) is extremely rapid and is much higher than in the c direction. O_2 is therefore proposed to diffuse along the a-b planes until it reaches the lateral Ag-sheath, which then adsorbs the oxygen and transports it to the tape edge where it returns to the atmosphere [30].

A second driving force for texturing in BSCCO is the anisotropic crystal growth rate of Bi-2223 which produces large-aspect-ratio plates during annealing.

2.2.4 Sausaging and Core Thickness

The degree of texturing is greatest at the Ag/HTS oxide interface and decreases with distance into the oxide layer, away from this interface. This may explain why thinner tapes possess higher J_c. However, it may also be that the self-generated field of the oxide is at least partly responsible for the reduction in J_c for thicker oxides.

Whatever the precise reason, tapes with thinner core thickness possess higher J_c and are therefore desirable. However, the onset of the "sausaging" defect, which impedes current flow and reduces J_c, can frustrate efforts to reduce the core thickness.

Sausaging is a defect whereby the Ag-sheath/Bi-2223 interface becomes unstable and appears wavy. it is quantified as the ratio of the average roughness of the Ag/Bi-2223 surface to the average Bi-2223 thickness [31]. Sausaging reduces J_c because it reduces the degree of alignment in the oxide grains, and because in regions where the oxide core is narrower, greater current is carried by the Ag sheath. Because the sheath is non-superconducting, the overall J_c of the tape is reduced - a process known as "current sharing."

The onset of sausaging represents a limit to the total deformation a tape may be subjected to during the rolling stage of the OPIT process. It therefore places a limit on how thin the tape, and its superconducting core may be. Sausaging-onset is a function of many possible processing variables in the OPIT process such as the initial drawn wire diameter, the powder density, deformation strains during each rolling pass, roll diameter, strain rates, annealing steps, the number of filaments and their diameter.

The extreme malleability (H_v=33) of the high-purity Ag sheath, as compared to the hard ceramic core (H_v=120) is a major contributor to the susceptibility of sausaging. Alloying the Ag sheath with tiny fractions of Mg and Au greatly increases the sheath hardness and therefore greatly reduces the sausaging problem by promoting a smoother interface [32]. However, alloying elements will affect the J_c properties, usually detrimentally, and a trade-off must be made.

The fill factor may affect sausaging. For multifilamentary tapes, sausaging was reduced for lower fill-factor tapes [33].

For low-temperature superconductors, sausaging has been eliminated by hot isostatic pressing.

2.3 Microstructure

2.3.1 Defects

Studies on the individual filaments within a tape suggest multiple, independent mechanisms operate at different length scales to limit the current.

"Vortex pinning" within grains is the smallest length scale defect and serves to establish a fundamental upper limit on $J_{c.}$

Weak or non-superconducting grain boundaries are believed to be the major limiting factor in the J_c of BSCCO tapes [34]. The remaining "strong," superconducting grain boundaries are believed to carry the current. High J_c tapes have been observed to possess platelet grains longer than those of lower J_c tapes. This would result in less grain boundary area *per* unit length of tape - the electrons need traverse fewer grain boundaries per unit length. As the platelet-grains grow, they will also seek lower-energy grain-boundary configurations such as low-angle tilt boundaries which would be better connected electrically [34].

Conductivity within grains of Bi-2223 is non-isotropic: the conductivity along the a-b planes is significantly higher than along the c-axis - c-axis flow is flow between Sr-O/Bi-O layers. For a 200 µm long filament, c-axis flow was estimated to be from 0.5 to 1.5 µm, or up to 0.75% of the length [14].

On a larger length scale, crack formation in the filaments interferes with the longitudinal current flow and diminishes the effective filament conducting area. Cracks are formed during the intermediate rolling stage where the HTS oxide in the tape is densified. Improved tape processing is expected to offer scope for improvement of this defect [14]. Studies comparing rolled and pressed Bi-2223 tapes illustrate that for pressed tapes cracks propagate longitudinally along the tape axis. However, for rolled samples cracks are transverse to the conducting path. [1]. Not surprisingly, pressed samples possess higher J_c than comparable rolled samples - see table 4. Unfortunately, pressing is not conducive to mass production.

2.3.2 Linking and Flux Pinning

"**Weak-link**" behavior and "**flux pinning**" behavior of HTS materials are the two most important manifestations of their microstructure in terms of explaining their J_c/magnetic field properties at high-temperature (77 K).

YBCO has been credited with possessing much stronger flux pinning at high temperatures than Bi-2223. Unfortunately, YBCO is plagued by a weak link defect which has stymied efforts to develop a continuous manufacturing process for YBCO tapes. In a frustrating irony of nature, the reverse situation exists for Bi-2223 in that it suffers poor flux pinning but does not suffer as severely from weak links.

Regarding BSCCO-Ag tape, in 1991 Martin Maley wrote:

" ...the advantages of YBCO in its smaller degree of anisotropy and stronger flux pinning at high temperature promise superior performance if weak links can be overcome."

"...at present the weak flux pinning problem renders the best of these materials (BSCCO-Ag tape) virtually useless for most applications above 20 K." [11]

The weak flux pinning problem of Bi-2223 therefore confines it to applications entailing negligible external magnetic field. Transmission cable has been identified as just such a low-magnetic-field application [13]. Of course a HTS cable would still be subject to its own "self" magnetic field which undoubtedly impacts on its properties.

The most promising approach to resolving the weak link problem is by promoting a highly textured plate-like microstructure which promotes current flow mainly along the well-conducting Cu-O planes. Bi-2223, thanks to the large separation between its easily cleaved Bi-O layers (0.3 nm), inherently possesses a micaceous structure that promotes texturing upon rolling, Texturing here refers to grain allignment in the a-b plane [11]. This texturing is believed to be the major reason for high J_c in Bi-2223 tapes [27].

Therefore, the micaceous structure of Bi-2223 uniquely suits it to the OPIT process, and therefore to mass production. This self-aligning capability of the Bi-O double layer in Bi-2223 is the major reason they are the only HTS poised for commercialization [1].

2.3.2.1 Improving Flux Pinning

Introduction of artificial defects to act as pinning centers in Bi-2223 can greatly increase the J_c/H-field performance. Neutron irradiation and heavy-ion irradiation have been used to introduce defects [as cited in 35]. Additions of other elements such as Ti, Zr, Hf, or particles of MgO or $SrSO_4$ have also been tried in order to introduce amorphous planar defects [36].

It has also been demonstrated that defects introduced by mechanical deformation act as pinning centers. This is likely as a result of greater dislocation density produced during processing [35]. However, the scope for improvement in flux pinning using mechanical deformation may be limited by the danger that too much mechanical damage could introduce weak links, because of the short "coherency length" of Bi-2223 conductors.

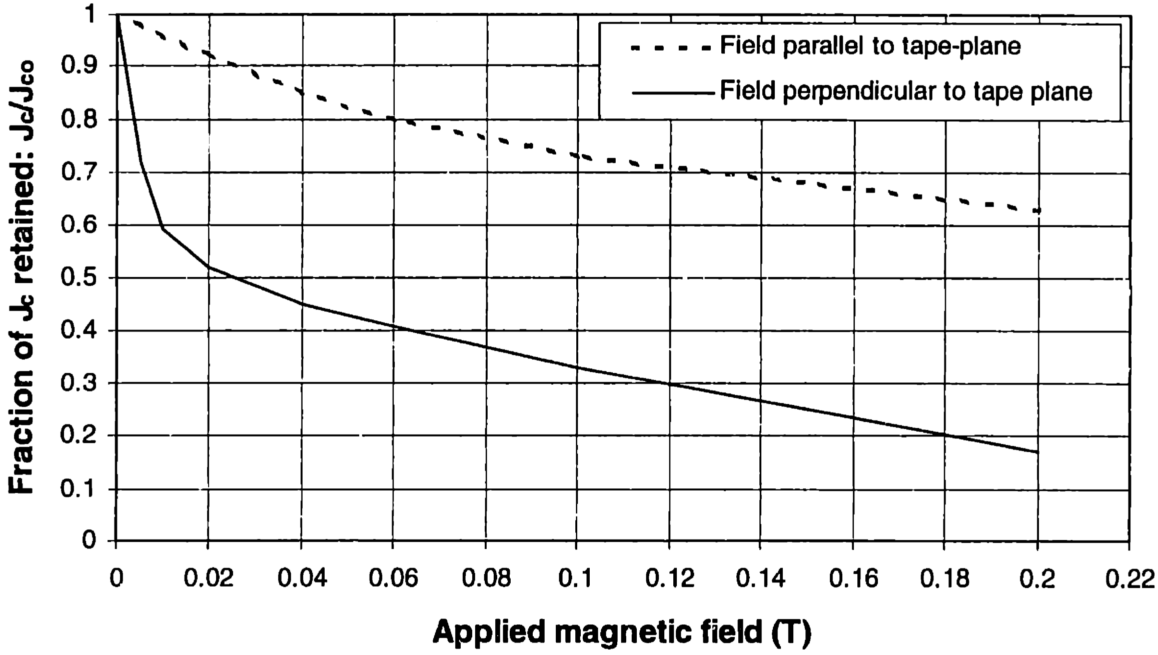
2.4 Tape Properties

2.4.1 Magnetic Field Behavior

The J_c of a Bi-2223 tape is critically dependent on both T and H (applied magnetic field.) At 77 K, the J_c of Bi-2223 is seriously compromised by application of even small external magnetic fields.

Figure 5 illustrates a typical example of the severity with which externally-applied magnetic fields compromise the J_c of Bi-2223, and how very anisotropic the Bi-2223 is. Magnetic fields applied pependicular to the tape surface (or parallel to the c-axis of the Bi-2223 lattice) is so devastating to the J_c of Bi-2223 tapes that it is difficult to imagine any application at liquid nitrogen temperatures where the device might even accidentally be exposed to such a field. Even a typical kitchen magnet, of about 0.02 Tesla could cut J_c by about half. One need only imagine the glee of a small child armed with a magnet upon discovering his ability to cut off the power of an entire city by affixing his toy to a HTS power transmission cable in order to appreciate the kind of engineering precautions which would be necessary.

Figure 5: Retention of J_c under external magnetic field


ref. [22]

The coupling strength between superconducting CuO_2 planes is believed to explain, in part, the location of the irreversibility line. The closer the CuO_2 planes, the better the coupling [27].

TABLE 5 - Inter-CuO_2-Plane Spacing

Material	Distance between parallel CuO_2 planes. (nm)
Y-123	0.84
Tl-1223	0.88
Bi-2223	1.23

2.4.2 Increasing the Fill Factor

Due to mismatch in the coefficient of thermal expansion between the Ag sheath and the HTS oxide core, cooling the tape from its original processing temperature of typically 840 C to 77K will place the Ag sheath in tension and the Bi-2223 filaments in compression. Reducing the Ag:HTS ratio (increasing the fill factor) will therefore reduce the compressive stress experienced by the HTS core. Studies on etching away the Ag sheath for Bi-2212 tapes suggest that a gain of 50 to 120% in J_c is possible by reducing the Ag-sheath thickness [31]. However, this insight is of limited practical value for increasing tape J_c since a certain thickness of Ag-sheath is essential to provide mechanical support to the HTS during manufacture, and to enable handling, winding and prevent fracture of the HTS.

A competition exists between J_c and the tape fill factor. Fill factor may usually only be increased at the expense of J_c. In the same vein as the previous paragraph, the fill factor cannot be increased without limit because an Ag-sheath is required to sustain the tensile stress during the wire drawing stages of tape processing and for the cable manufacturing stage where the tape is wound about the cylindrical former. The HTS powder cannot sustain tensile stress, so increasing the fill factor too much would risk wire breakage during the wire drawing stage.

"***Thus continued progress toward higher J_{eng} must come largely from increases in J_c.***" [33]

As will be seen in chapter 4 and figure 10 in particular, this conclusion is of great consequence to the economics of HTS cables.

2.4.3 Strain

It is a common conception that the overriding barrier to the usefulness of superconductors is their extreme brittleness, rendering their practical use impossible. Handling and forming HTS tapes into practical devices will require the tape sustain a certain applied stress and bending bend radius. During handling this occurs when the tape is wound onto a storage cylinder. For cable applications most designs involve helically winding the tape around a "former," or tube, through-which liquid nitrogen would pass for cooling. From an engineering point of view it is therefore important to understand how tape properties degrade with strain. The maximum tensile strain on the outer edge of tapes is given by:

(eqn. 2.4.3-1) $\varepsilon_{tape} = t/2R$ where t is the tape thickness and R the bend radius.

When wrapped about a cylinder as in cable manufacture the strain is as follows:

(eqn.2.4.3-2) $\varepsilon_{wrap} = (t/2R_{former})\times(\cos^2(90^\circ-\theta))$

θ is the wrapping angle of the tape with respect to the axial line of the cylinder, so 0° would mean the tape lay parallel to the tube.

Thinner tapes therefore experience less strain when wrapped about the same radius.

Experiments show that after a critical strain has been reached, ε_{irr},the tape experiences a sharp loss of about 50% in J_c followed by a more gradual drop at higher strain levels. It is therefore vital that this "irreversible" strain not be surpassed during application.

TABLE 6 - Examples of Critical Strain

Type of Tape	Critical Strain
multifilamentary	.01 [37]
monofilamentary	.002 [37]

Multifilamentary tapes have demonstrated superior resistance to strain degradation of J_c than have monofilamentary tapes. This is one of the reasons why development efforts have focused increasingly on multifilamentary tapes. In addition, thinner core size promotes ε_{irr} as does increasing the filament count in the tape [3,22].

The fill factor has a pronounced impact on strain properties - as fill factor decreases, ε_{irr}, increases. This is important because it serves to further explain the difficulties in producing high f.f. tape [37].

2.4.4 Length-Dependence of Current Density

The J_c of a Bi-2223 tape decreases with the logarithm of its length. This behavior contrasts sharply with the behavior of low-temperature superconductors or with traditional copper or aluminum conductors which are isotropic and would display the same current density, regardless of length, for a fixed (1µV/cm for example) potential gradient.

This length-dependence of J_c is potentially one of the most serious problems facing HTS tapes. The results from many researchers have been compiled and presented in figures 6 & 7. The length-dependence of J_c is so pronounced that it suggests a <u>sample-length convention</u> should be adopted by the HTS research community when reporting J_c. Moreover, apart from J_c, what is of critical importance in characterizing the J_c of a Bi-2223 tape is its <u>coefficient of length degradation of current density</u> (C_{LDJ}) as per the following equation:

(eqn. 2.4.4-1) $J_{c,x} = -C_{LDJ}\ln(x) + J_{c,1m}$

Fig.6 : Effect of Tape Length on J_c

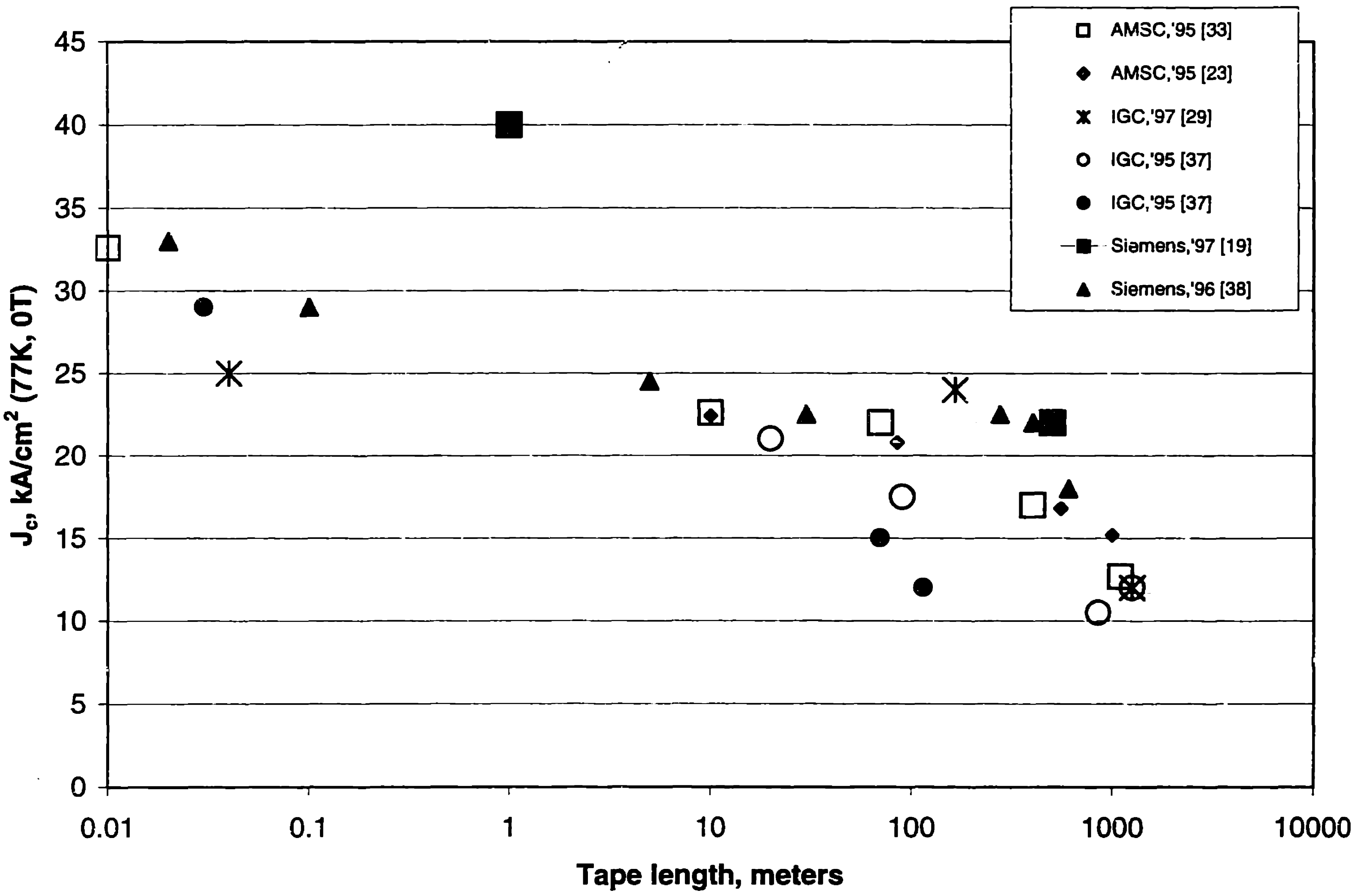


Fig.7 : Effect of Tape Length on J_c

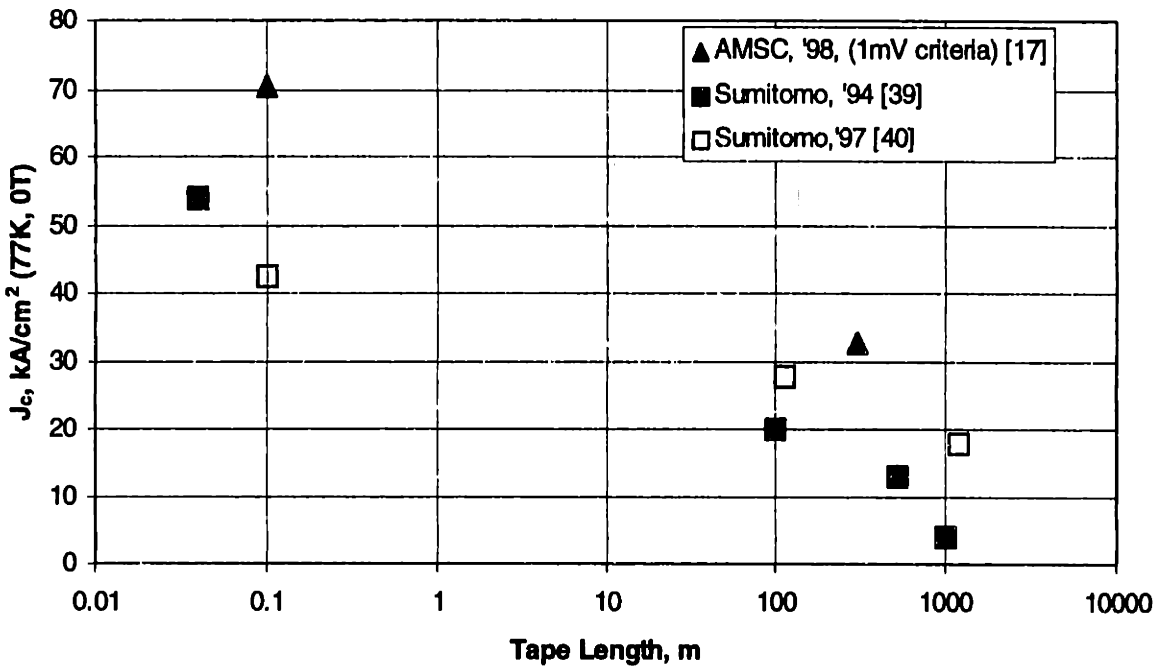


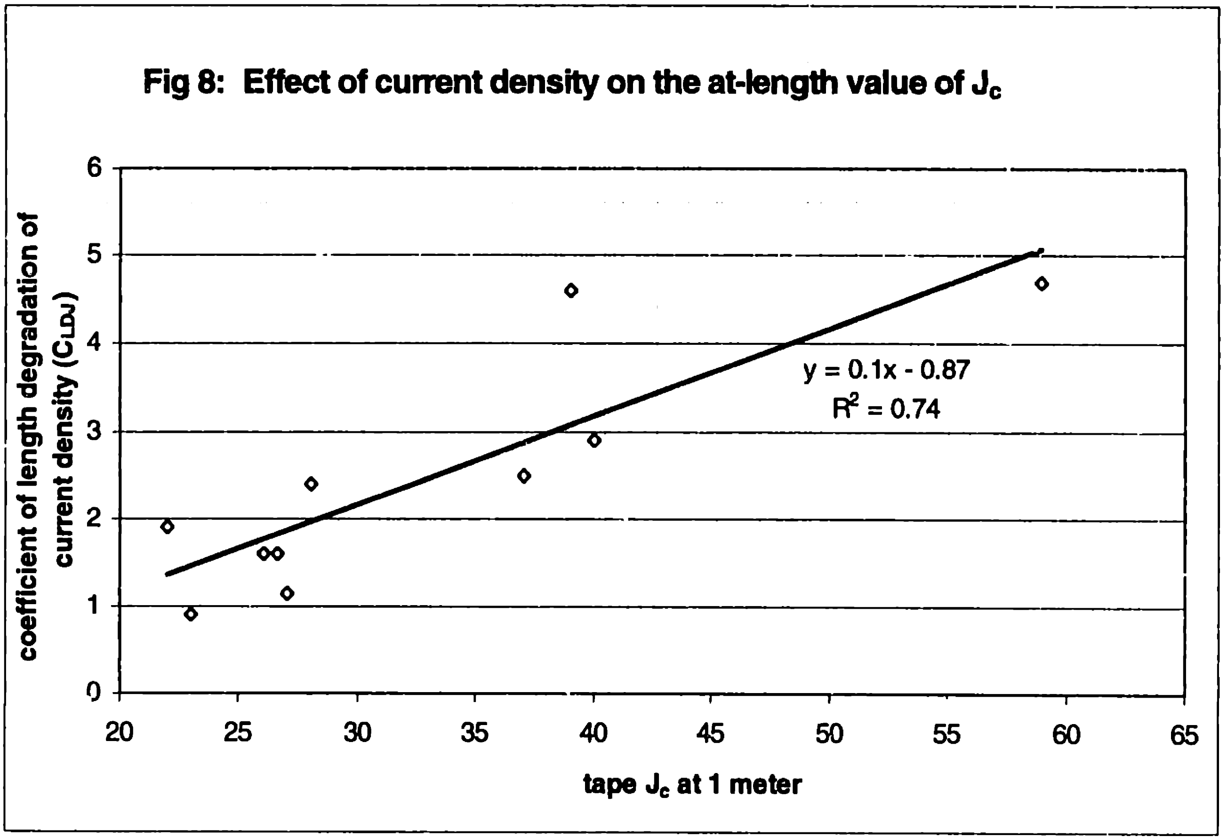
Table 7 - Effect of J_c on the at-Length Properties of J_c

(from figures 6 & 7)

Tape Manufacturer and Year of Result	C_{LDJ}	$J_{c,lm}$ kA/cm^2
AMSC '95	1.6	26
AMSC '95	1.6	26.6
IGC '97	0.9	23
IGC '95	2.4	28
IGC '95	1.9	22
Siemens '97	2.9	40
Siemens '96	1.15	27
AMSC '98 (1mV/cm criteria)	4.7	59
Sumitomo '94	4.6	39
Sumitomo '97	2.5	37

2.4.4.1 Apparent Dependence of Length-Dependence on J_c

Is it possible that C_{LDJ} *increases* as a function of $J_{c,1m}$? Figure 8 illustrates a regression of the data from table 7.



The high R^2 of 0.74 suggests there is a relationship. If this is in fact the case then the empirical equations 2.4.4.1-(1 to 3) are implied; and with a very important consequence:

Short-length values of J_c would need to be a ***multiple*** of the desired long-length design value of J_c, which would necessitate far greater advances in short-length J_c than otherwise might have been expected. For example, to realize a desired 1000-m value of J_c would require, from 2.4.4.1-3, the J_c at 1 m be ~3 times higher. The multiple would be increased for longer lengths, and a cap could even exist on the maximum application length depending on the J_c behavior of long, kilometer-scale tapes.

(eqn. 2.4.4.1-1) $C_{LDJ} = 0.1 \times J_{c,1m} - 0.87$

(eqn. 2.4.4.1-2) $J_{c,x} \approx -(0.1 J_{c,1m} - .87)\ln(x) + J_{c,1m}$

(eqn. 2.4.4.1-3)

multiple of $J_{c,1m}$ necessary to realize desired J_c-at-length ~ $\dfrac{1}{1 - 0.1 \times \ln x}$

Despite the compelling evidence of figure 8 that C_{LDJ} increases with $J_{c,lm}$, it should be cautioned that this is not a scientific finding. It is only based on a tabulation of values from the literature examined during this study. This study therefore recommends a deeper scientific analysis of the relationship between C_{LDJ} and $J_{c,lm}$.

Chapter 3
Alternating Current Losses

It is a common belief that superconductors, by definition, conduct electricity with absolutely no energy loss whatsoever. In fact, all superconductors experience losses when transmitting an alternating current. Zero-loss transmission occurs only for direct-current (DC) transmission. As most power applications involve AC current, AC losses are a serious problem. The losses must be sufficiently low to justify the greater energy and cost required to remove the heat generated at 77K using liquid nitrogen. The reduction and characterization of AC losses is a major focus of HTS research into tapes and cables, and is viewed as one of the key requirements for commercialization [41].

AC losses arise due to the energy barrier which must be overcome in changing the direction of currents and fields established by current flow in the opposite direction. These are known as "hysteresis" losses. AC losses are amongst the least-understood operating parameters of HTS [42]. The following shall sketch the highlights of current knowledge relevant to the evolution of HTS tape technology.

For the frequencies of power transmission assumed for the following, 50 to 60 Hz, the energy loss *per AC cycle* is generally independent of the AC frequency for BSCCO tapes so long as the peak current is less than I_c [42]. This frequency independence is considered accurate for frequencies below 1000 Hz [43]. The losses would then be mainly hysteresis losses.

3.1 Tapes

AC losses are highly dependent on the shape of the conductor. For tapes, the loss *per AC cycle* per unit length are closely predicted by the "Norris" equations for elliptical and thin-strip tape cross sections. Data from research on AC losses in tapes nearly always lie on, or between the values predicted by these two Norris equations. Multifilamentary tapes usually well-fit the Norris ellipse equation. The Norris equations are accurate when the peak current of the AC cycle, I_{pk}, is < I_c. The "Norris" equations [44] are :

For an ellipse:

(eqn. 3.1-1)

$$Q_{ac} = \frac{\mu_o I_c^2}{\pi}\left[\frac{(2-i)i}{2} + (1-i)\ln(1-i)\right]\times f \text{ W/m}$$

For thin strips:

(eqn. 3.1-2)

$$Q_{ac} = \frac{\mu_o I_c^2}{\pi}\left[(1+i)\ln(1+i) + (1-i)\ln(1-i) - i^2\right]\times f \text{ W/m}$$

(eqn. 3.1-3)

$$i_{tape} = \frac{I_{pk}}{I_c}, \text{ (ratio of the peak AC current to the DC critical current.)}$$

I_{pk} is related to the root mean current as follows:

(eqn. 3.1-4)

$$I_{rms} = \frac{I_{pk}}{\sqrt{2}}$$

The following simplified versions of the Norris equations more clearly illustrate the exponential dependence of losses on the current ratio (i). They are within 25% of the Norris equations between $0.05<i<0.95$.

Ellipse:

(eqn. 3.1-5)

$$Q_{ac,tape} = 1.31\times10^{-7} I_c^2 i^{3.3} \times f \text{ W/m}$$

Thin Strip:

(eqn. 3.1-6)

$$Q_{ac,tape} = 1\times10^{-7} I_c^2 i^{4.2} \times f \text{ W/m}$$

f, the AC frequency, is 60 Hz for North American power lines.

A trade-off must be weighed between AC losses vs. total power transport, operating temperature and other engineering factors. Transporting the same current on tapes with higher I_c is another obvious strategy for reducing AC losses, [45] but at greater cost of HTS tape.

Real tapes exhibit behavior ranging from strip-like to ellipse-like. The ellipse Norris equation is usually an excellent fit for multifilament tapes while AC loss from monocore tapes may lie anywhere between strip or ellipse behavior [46]. The strip-type behavior is obviously more desirable for reducing AC losses. It is not understood how to induce tapes to conform to strip-type behavior as it is not simply a question of cross section shape as the equation nominally might suggest.

3.1.1 Eddy Current Losses

An alternating current within the HTS oxide will generate alternating magnetic fields which will induce eddy currents within conducting materials in the vicinity. Thus, eddy currents develop in the silver sheath of the tape and cause resistance heating to occur as per ohm's law. However, it has been shown that these "silver losses" are much smaller than the hysteresis losses of the HTS [47].

3.1.2 Measuring AC Losses

It is important to distinguish between AC losses measured through application of an externally-applied alternating magnetic field, which then couples with the HTS to generate an "induced" AC current, and AC losses arising from an AC "transport" current which actually flows through the tape, giving-rise to the "self" magnetic field of the tape. The latter is the more relevant to understanding how tapes would behave in actual HTS cable applications whose whole purpose after all is to transport current under self-field conditions [47]. The highly anisotropic nature of Bi-2223 makes it difficult, if not impossible, to measure the actual transport, self-field AC losses by applying an external AC magnetic field [48].

3.1.3 AC Losses in Multifilamentary Tapes

There is much debate over whether multifilamentary tapes possess lower AC losses than monocore tapes. In theory the losses should be reduced from those for a monocore sample by 1/N, with N being the number of independent filaments [49]. However, the filaments are not independent because an induced coupling current will flow through the silver matrix between the filaments. Because the resistivity of silver is very low at 77K, there would seem little scope for improving the AC losses.

An experimental process involving introduction of high resistivity $BaZrO_3$ films into the Ag sheath matrix to act as a current barrier between filaments was observed to reduce AC losses by a factor of ten. Unfortunately, the J_c was lower by a factor of at least two [50].

A theoretical analysis of HTS AC losses makes clear that non-twisted multifilamentary tapes will not improve the AC loss characteristics of the tape. Losses may even increase with them as compared to a monocore tape having the same fill factor and tape cross section – the increased loss is expected to be at least in proportion to the greater core area needed to accommodate the filaments. Furthermore, for transport currents, the loss is independent of the filament diameter [45].

A study comparing losses of monofilamentary tapes to multifilament tapes shows AC losses in multifilamentary tapes are much higher – about 2.2 times higher [43]. The cause is blamed on the magnetic coupling between filaments creating mutually-induced magnetic fields and hence a strong interaction between filaments. Other studies have suggested no difference between mono and multifilamentary tapes [48].

Twisted multifilamentary tapes can, *theoretically*, reduce the AC losses due to *externally* applied magnetic fields if the twist pitch is less than the skin depth of the silver sheath, which is approximately 3 mm at 50 Hz and 77K. It is not clear whether such a high degree of torsional deformation is possible on the final pre-rolled wire produced from the OPIT process. [45]. Other authors have argued that twisted filament tapes do reduce AC losses [33,42].

The debate would seem settled by a recent study comparing transport AC losses in twisted and untwisted multifilament tapes. Both demonstrated ellipse-type losses, with the twisted tapes actually having slightly higher AC losses. The paper concludes:

"*...the key factor which dominates AC transport losses ... is I_c, nearly independent of the superconductor geometry or the number of filaments.*" [50]

In order for multifilamentary tapes to magnetically decouple and improve their self-field AC loss behavior, the filaments would need to be transposed, [45] which is a far more complicated braid-like pattern than a simple twisting-type deformation can possibly provide for. This author knows of no published work involving the manufacture of transposed-filament tapes, although prototype transposed-tape HTS cables have been manufactured with the aim of reducing the self-field transport AC losses.

3.2 Correlating Tape Properties to Cable Properties

3.2.1 Current Density

To be useful, HTS tape must be incorporated into cable.

The HTS cable will *always* have lower current carrying capacity than what one would expect from summation of the I_c values of all the tapes from which the cable is constructed. This behavior is unlike normal copper or aluminum conductors where the total equals the sum of its parts - HTS behavior is non-isotropic.

There are two major reasons for this degradation of the J_c. Firstly, the self-magnetic field of the cable is different from that of an isolated tape, thereby lowering the tape J_c, to perhaps 75% of its original J_c [52].

Secondly, the tape will experience some strain-degradation of J_c due to their handling and incorporation into the cable, degrading J_c to perhaps 80% of its original J_c [52].

These factors are reflected by the retention fraction, F_R - the fraction of tape I_c retained upon inclusion into a cable. A typical value is 0.6. Appendice 1 tabulates this important parameter for several prototype HTS cables. An "ideal," or "perfect" HTS cable would have $F_R = 1$.

(eqn. 3.2.1-1) $F_R = F_{field} \cdot F_{strain}$

(eqn. 3.2.1-2) $I_{c,cable} = N \cdot F_R \cdot I_{c,tape}$

N is number of tapes in the cable.

3.2.2 Length

For each tape incorporated, greater than one meter of tape is usually required to produce one meter of cable. This is because most HTS cable designs involve wrapping the tape around a cylindrical former at some lay angle. The number of times greater tape-length required per meter of cable is given by:

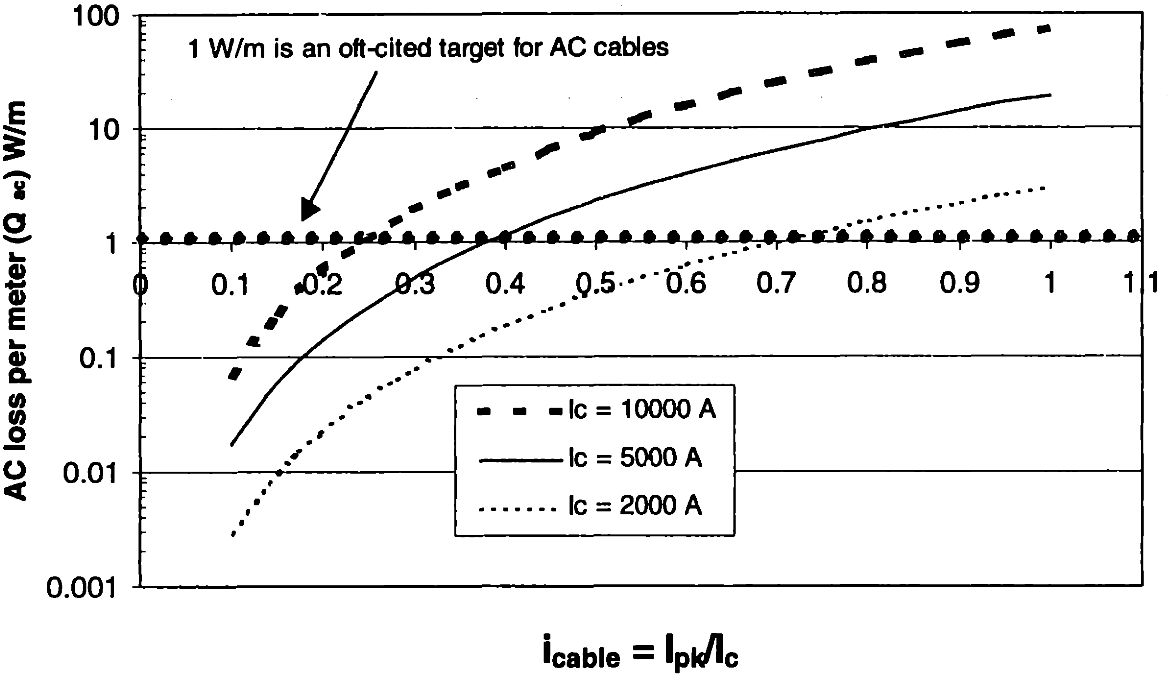
(eqn. 3.2.2-1) Tape-Length Multiple (TLM) = $1/\cos(\theta)$

An "ideal" cable would then have a θ of 0^{o}, consuming only 1 meter of tape per meter cable.

3.3 Cables

The AC-loss problem is summarized in figure 9. In order to realize the benchmark AC loss of 1 W/m, high-I_c cables may only operate at only a fraction of their capacity, thereby costing much more in terms of HTS tape. This would not be the case for a DC HTS cable. A DC cable could operate at a fixed fraction of the I_c regardless of how large I_c is.

Fig. 9: The Wasted Current Capacity of HTS AC Cables (for R_o/R_I = 1.1 & 60 Hz)



The AC loss behavior of HTS cable is slightly different from that of the tapes of which it is comprised because of the shape-dependence of AC losses. Losses for a tubular conductor are given by the following equation [54]:

(eqn. 3.3-1)
$$Q_{ac,cable} = \frac{\mu_o}{\pi} r^2 I_c^2 \left(\frac{i}{r} - \frac{i^2}{2r^2} + (1 - \frac{i}{r}) \ln(1 - \frac{i}{r}) \right) \times f \quad \text{W/m}$$

(eqn 3.3-2)
$$r = \frac{x^2}{(x^2 - 1)}$$

(eqn. 3.3-3)
$$x = \frac{R_o}{R_i} \quad \text{(ratio of the outer to inner radii of the HTS conductor surface)}$$

(i) in equation 3.3-1 is simply the current ratio given by:

(eqn. 3.3-4)
$$i_{cable} = \frac{I_{pk,cable}}{I_{c,cable}}$$

During this study, the following empirical approximation to equation 3.3-1 was developed, making the relationships clearer:

(eqn. 3.3-5)
$$Q_{ac,cable} = 0.098 \mu_o I_c^2 \ln(x) i^3 \times f \quad \text{W/m}$$

For $0.05<i<1$, equation 3.3-5 is within:
- 10% of equation 3.3-1 for $1<x<1.22$, and:
- 32% of equation 3.3-1 for $1.22<x<1.5$

3.3.1 Current Density Homogeneity

Because AC losses scale with the cube of current, they will be far magnified if there is uneven current distribution within the tapes of the cable - (i) could even exceed one. In fact it is often reported that current preferentially flows in the outer layers of the cable. A characteristic of cable prototype development is therefore to examine different tape wrapping configurations. Transposing the tapes is the most effective means to ensure that each tape carries the same current, but it is expensive because of the complicated braiding pattern which requires that "*each tape occupy each position in the cable as often as every other tape.*" [12]

3.3.2 Eddy Current and Resistive Losses

HTS cables experience eddy-current and resistive losses during AC operation. Eddy current losses are insignificant for transmission frequencies (50-60 Hz). Resistive losses can become important at high curent levels -as I_{pk} approaches the cable I_c. Danish researchers demonstrated that resistive losses could rise to 25% the size of the hysteresis losses as (i) approaches 1 [55].

3.3.3 Relating Tape and Cable AC Losses

It is the AC loss of the final HTS transmission cable which is really important. However, because much research is devoted toward understanding the AC properties of HTS tapes, it is valuable from a design perspective to understand how the two would be related: would the AC loss of the cable be greater or less than that of the HTS tapes from-which it is made?

If the same root-mean-square current transported by the cable were instead transported by the N separate, isolated tapes, it is simple to derive that i_{cable} and i_{tape} would be related as follows:

(eqn. 3.3.3-1) $$F_R \cdot i_{cable} = i_{tape}$$

Incorporating equation 3.3.3-1 into 3.1-5 and dividing by (3.3-5) gives the ratio of losses in a hypothetical conductor of N separate tapes to that of a cable comprised of the N tapes transmitting the same root-mean-square current. Armed with equation 3.3.3-2 one can interpret tape loss data to gain a rough idea of what kind of losses might be expected in a cable made of those tapes.

(eqn. 3.3.3-2) $$\frac{Q_{ac,tapes-equivalent}}{Q_{ac,cable}} \approx 1.07 \frac{i_{c,cable}^{\;0.3} F_R^{\;1.3}}{N \ln(x)},$$

Equation 3.3.3-2 shows that losses may be reduced in the cable by making the outer and inner conductor radius very nearly the same. If we assume $F_R = 1$ and that (i_{tape}) is actually to the power of 3 in equation 3.1-5, then equation 3.3.3-2 reduces to a handy rough-design criteria for designing a HTS cable having lower AC losses than the separate tapes which comprise it would have.

(eqn. 3.3.3-3) $$\frac{R_o}{R_i} < e^{\frac{1}{N}}$$

Equation 3.3.3-3 may be further:

(eqn. 3.3.3-4) $$R_o = t \times (\text{layers}) + R_i;$$

t is the tape thickness and "layers"is the number of tape layers in the cable.The design criteria becomes:

(eqn. 3.3.3-5) $$t \times layers < \frac{R_i}{N}$$

Chapter 4
Cost Competitiveness

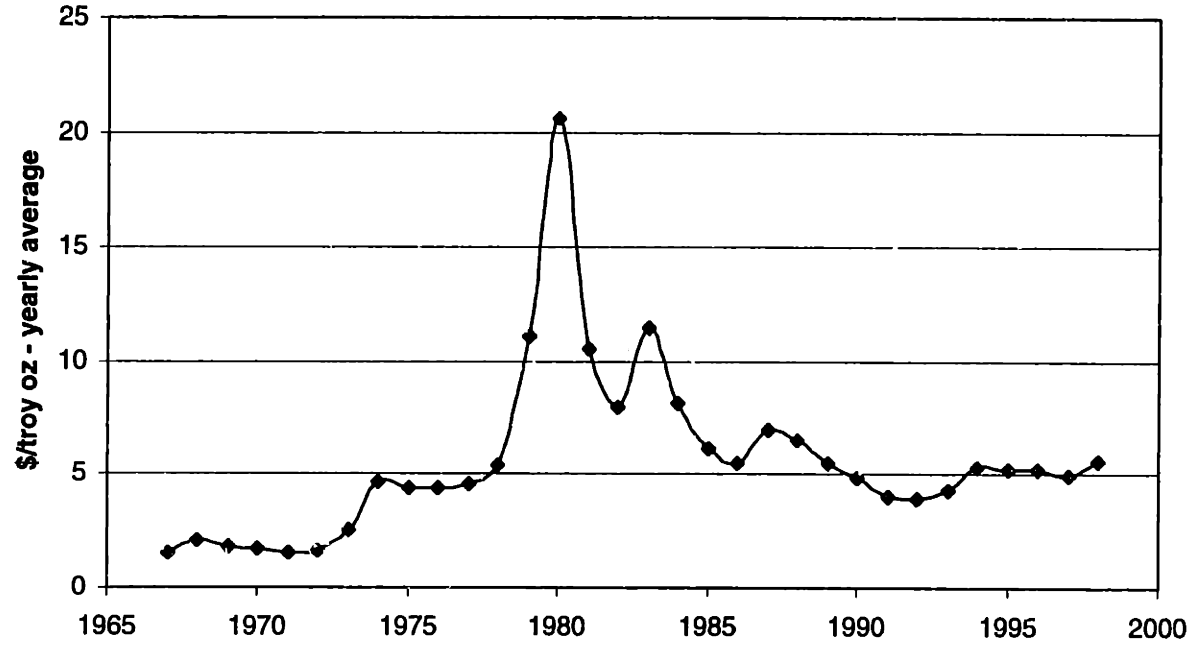
One need only imagine the conflicting objectives of different parties to a future HTS cable market in order to understand why the subject of HTS tape costs is a delicate one. Tape manufacturers want low costs for themselves, but want to be able, ultimately, to charge as much as practical while conveying potentially low cost such that interest in the technology is viewed as practical in the long-term. Cable manufacturers desire a low cost of tape so that it is only a small fraction of their total HTS cable cost. Cable buyers such as utilities might simply like to know the cost of the tape so they are in a better position to negotiate the cost of cable and assess the technology. Government donor agencies would like to see a low, or potentially low, or decreasing cost of tape so that they do not feel they are supporting a work of pure science fiction.

It is nevertheless possible, on the basis of reasonableness, and a knowledge of the technology, to state with greater than zero certainty, greater than nothing about tape costs. This should be insightful.

4.1 Silver Price

Silver metal is an indisputable cost component of HTS tape. Figure 10 illustrates the historical market value of silver. The average over the 10 year period from 1988 to 1998 has been $5.0 per troy oz (1 troy oz = 31.1 g), with a standard deviation of only 0.75. $5/troy oz is assumed in this paper unless otherwise stated.

Fig. 10: Historical Silver Price



The cost of silver for the Ag tubes used for the OPIT process is reported to be about $7 per troy oz *more* than the market price for Ag [56].

4.2 Cost Performance Benchmark

The kilo-ampere-meter is the most fundamental measure of transmission capacity. The cost of installing a kAm of transmission capacity is the most fundamental cost-performance benchmark facilitating comparison of costs between different transmission schemes.

The industry benchmark for adoption of HTS cables is $\$10/kA_{rms}m$ (or $\$10/kA_{dc}m$.) This is based on the cost of copper used as the conductor. For example, ABB's "M.I.N.D." cable is designed to carry a DC current of 1600 A over 20 cm^2 of solid copper [57]. With market price of copper now ~ $1/lb, this yields a "conductor-only" cost-performance-benchmark (CCPB) of $11/kA-m, which closely agrees with the above.

The CCPB refers to the cost of a *function* - namely the function of transporting current over some distance. It is implicitly assumed here that the cost of the conductor incorporated into a standard overhead line is mainly the market cost of raw copper. In fact the actual cost will be higher because some processing must be performed on the copper in order to transform it into the product which performs the function of the *conductor*. From section 4.7 we may deduce that the "true" CCPB for copper would be between $10/kAm and $20/kAm.

The conductor cost is only one component of the total cost of a traditional transmission line. In the case study of a proposed DC transmission line examined in section 7.4.2, the total CPB for the proposed HVDC line was \$59/kA$_{dc}$m, which includes all costs - materials, cable, installation, right-of-way; everything. The CCPB of copper therefore constitutes only ~ \$11/\$59 =19% of the total finished line cost. Resorting to a CCPB is therefore a crude measure of the ultimate competitiveness of HTS cable compared to a copper line - it assumes that all other costs would be identical, when they would not be. However, a CCPB has the advantage that it may be known with greater certainty, and perhaps this shall be enough by itself to assess the competitiveness of HTS cable. Other costs are dependent on issues unknowable a-priori, such as the cable design, and line installation costs.

4.2.1 Defining the "Conductor-Only" Cost Performance Benchmark for HTS Tapes

In a HTS cable, the product which performs the function of the conductor is the HTS tape. The CCPB for HTS cable would then be based on the **total cost of the HTS tape** incorporated into a HTS cable. This comprises both materials and manufacturing costs.

4.2.1.1 Base-Cost of HTS Tape

On a per-meter basis:

(eqn. 4.2.1.1-1) $C_{tape} = C_{Ag} + C_{Bi\text{-}2223} + C_{manufacture}$

(eqn. 4.2.1.1-2) $CCPB = C_{tape}/I_{max,tape}$

For DC transmission, $I_{max,tape}$ would equal I_c. In AC, $I_{max,tape}$ is the maximum root-mean-square operating current, which would be $0.7 \times I_c$. Hereafter we assume DC operation for simplicity.

Note: following assumes cross sectional area, A_{tape}, is in cm^2

(eqn. 4.2.1.1-3) $C_{Ag} = (A_{tape}) \times (1\text{-f.f.}) \times$ (100 cm/m) $\times$ (Ag density) $\times$ (market cost of Ag + cost premium for Ag OPIT tubes)

(eqn. 4.2.1.1-4) $C_{Bi\text{-}2223} = (A_{tape}) \times$ (f.f.) $\times$ (100 cm/m) $\times$ (final Bi-2223 density) $\times$ (cost of Bi-2223 precursor powder)

(eqn. 4.2.1.1-5) $I_{c,tape} = (A_{tape}) \times (\text{f.f.}) \times J_c$

4.2.1.2 Magnetic Shielding

Some AC cable designs incorporate a HTS layer outside the HTS conductor to provide magnetic shielding. While this layer does not transport current, it would significantly increase the HTS tape consumed by the cable to a *multiple* of that used by the conductor itself. However, because its presence is design-dependent, this factor has not been included in the following calculations. In one prototype 61 tapes were used for the conductor, and 57 for the shielding, which is almost double [58].

(eqn. 4.2.1.2-1)

M.S.M. = Magnetic shielding multiple = (total HTS tape used in the cable)/(tape used only for conduction)

M.S.M. equals 1 if no shielding is used.

4.2.1.3 Operating Level

The $10/kAm benchmark for copper assumes the copper is based on the maximum continuous operating level of the copper transmission line. However, the maximum continuous operating level (OL) for a HTS cable would need to be less than that indicated by the cable I_c.

This is a particularly serious concern for an AC HTS cable. Figure 8 makes clear that in AC mode the cable could operate at only a fraction of its total current capacity in order to maintain AC losses to a fixed level. The important variable here is (i) - the ratio of the peak current during the AC cycle to the maximum current capacity of the cable.

Provision must be made for the safety operating margin envisioned for the HTS cable - the cable capacity cannot be designed based on I_c - it can only be some fraction of I_c to allow for over-currents and faults.

(eqn. 4.2.1.3-1) $\quad$ O.L. = S.M.$\times$ i (for AC cables)

(eqn. 4.2.1.3-2) $\quad$ O.L = S.M. (for DC cables)

4.2.1.4 Profit

The $10/kAm benchmark for copper, by definition, represents the final market cost of the conductor. Provision must therefore be made for the gross profit margin (G.P.M.) expected by the HTS tape manufacturer, and also the cable manufacturer. High-risk, high-technology products require higher ultimate rates of return. What is desired is the markup factor (M.F.) - the ratio of revenue to cost of goods sold. Gross profit margin of 40 to 60% is typical in high-tech firms, which leads to a markup factor of from 1.6 to 2.5.

(eqn. 4.2.1.4-1) $\quad M.F. = \dfrac{1}{1-G.P.M.}$ =(revenue)/(cost of goods sold)

4.2.1.5 Total Conductor Cost Performance Benchmark of HTS cable

Because the CCPB is based on the cost of conductor incorporated into the cable, the current density retention fraction F_R, and θ, the lay angle, must be accounted for as per sections 3.2.1 and 3.2.2.

(eqn.4.2.1.5-1)

$$CCPB = \left(\frac{1}{F_R \cos\theta}\right) \times \left(\frac{(M.S.M.) \times M.F._{tapes} \times M.F._{cable}}{O.L.}\right) \times$$
$$\left(\frac{100 A_{tape}\left((1 - f.f.)\rho_{Ag}(P_{Ag,market} + P_{Ag,processing}) + (f.f.)\rho_{Bi-2223} P_{Bi-2223}\right) + C_{manufacture}}{A_{tape}(f.f.) J_c}\right)$$

FR = 0.65, $\theta = 30^\circ$, M.S.M. = 0, $M.F._{tapes} = M.F._{cable} = 1.6$ (assumes gross profit margin of only 37.5%), and O.L. = 0.8 would be conservative, yet fair, parameters to incorporate into the first two brackets in the above equation. Together they increase the CCPB by a factor of 5.7 (8 for AC applications) over the nominal CCPB of tape as given by the 3rd bracket.

4.2.2 Interpreting Reported Values of the "Conductor-only" CPB

Because it is instructive, and ties together much already covered, the following shall interpret an industry-reported value of the CCPB for HTS tape.

In a recent paper authored by fourteen scientists of American Superconductor Corporation, a company intensely involved in the development of HTS tape, a CPB, of $7.5/kAm for an AC-applied Bi-2223 tape was reported. It was based on the silver cost only. The tape had J_c of 70 kA/cm^2 (1 mV/cm criteria). f.f.=0.35 , and dimensions 0.08×1.78mm. $5.5/troy oz Ag was assumed [17]. If the tape were used for DC applications, the reported CCPB would be $5.2/kAm - half the $10/kAm of copper. While this could only have been intended as a kind of "ball-park" figure, this thesis has now laid the groundwork to assess why the actual CCPB would be significantly higher, and for the following reasons:

1) The J_c of 70 kA/cm^2 is overstated, potentially greatly overstated, because its measurement was based on a 1 mV/cm criteria. As per section figure 3, the gradual transition out of superconductivity means that current will continue to increase with voltage. The HTS industry standard is the 1 μV/cm criteria - 1000 times lower than the voltage at which the 70 kA/cm^2 was recorded.

2) As per section 2.4.4, J_c for an application-length tape would be considerably lower. The reported 70 kA/cm^2 was based on a "short" sample size ~ 10 cm. However, most power transmission applications involve longer distances than this. Figures 6 and 7 show that J_c declines materially with distance.

3) The CCPB refers to the cost of the conductor incorporated into the cable. However, as per section 3.2.1, the "effective," or "retained" tape J_c is always lower upon incorporation into a cable.

4) As per section 3.2.2, more than one meter of tape* is required to manufacture a meter of cable. This is because the tape is typically wrapped at some angle around a cylindrical former. This will make the CCPB higher.

*That is, on a per-tape basis, since a cable obviously incorporates many separate tapes.

5) Silver processing costs, cost of the Bi-2223 powder, and tape manufacture costs were not included but will significantly increase the tape cost, as will profit-margin and operating safety margin.

The actual *partial* materials CPB would probably be greater than $5.2/kAm × 5.7= $30/kAm.

4.3 Manufacturing Cost of HTS Tape

In what follows, the cost of manufacturing the tape, not including the materials costs, is investigated.

4.3.1 Upper Bound

American Superconductor Corp., (AMSC on the Nasdaq stock exchange) is intensely involved in developing near-mass-production-scale HTS tape manufacturing processes and they routinely manufacture kilometer-scale lengths of HTS Bi-2223 tape with the OPIT process. AMSC is as close to a "pure-play" on HTS industrial-scale tape manufacture as one can hope for. An estimate of AMSC 's cost of tape production would therefore be of interest in estimating the cost of manufacturing tape on a per-length basis.

It is assumed the manufacturing cost of the tape is independent of the tape J_c since the general steps of the OPIT process would be similar regardless of J_c.

AMSC boasted production of over 120 km of tape in 1996 [19]. From this one may calculate with certainty an absolute upper limit on tape cost per-unit-length. Table 8 shows AMSC 's 1996 costs (pre-merger) [59]. We can therefore state unequivocally that manufacturing costs would be less than $12.6 M/120,000m = $105/m. In fact the processing costs would be substantially less since AMSC does not devote 100% of its resources toward tape manufacture - they also develop HTS devices and conduct research. If they devote just 10% of their expense to tape manufacture then manufacture cost is $10/m.

TABLE 8 - Breakdown of AMSC Expenses for 1996 Source: AMSC 10K SEC Filing	
	$, millions
Cost of Revenue	7.3
Research & Development	5.3
Selling & Administration	3.3
Total Operating Expenses	16
Cost of Revenue + R & D	12.6

4.3.2 Lower Bound

In a recent paper authored by fourteen AMSC scientists [17], it was suggested that total manufacturing costs would include labor, powder manufacturing, billet packing, deformation, heat treating, and electrical testing. They declared:

> *"... these costs must be kept at 50% or less of the silver costs, even as the HTS fill factor and Jc are further increased... We believe this is possible.* " [17]

The tape described in this paper was 0.08×1.78mm with f.f.=0.31. The market-cost of silver for such tape would be $0.165/m, which means they envision as achievable, scaled-up manufacturing costs of $0.08/m.
The silver metal in a typical 0.25×3mm, 0.3 f.f. tape costs approximately $0.88/m.

4.3.2.1 Case: Steel Product Manufacturing Cost

The production of steel products involves metallurgical processes similar to those of the OPIT process - rolling, heat treating, quality control. The manufacturing cost per meter of steel products shall therefore be examined.

Steel is a near-commodity business mass-produced world-wide. Steel is manufactured in a technically mature, automated production environment, in some cases requiring less than a single man-hour per ton of finished product. It is therefore seems likely that some time will be required before HTS tape manufacturing costs begin to approach the cost of a *comparable* steel product.

Materials cost are not included in the following estimate, the comparison is being made on the basis of processing costs only.

Steel Dynamics (STLD) is a highly efficient mini-mill producer. It is of interest here because its production is exclusively to steel sheet ranging from 0.04 to 0.5 inches thick by 40 - 62 in. wide. In 1997 their cost of goods sold was $330 M, for an output of 1.2 M tons (1 ton = 2000 lbs). Approximately 52% of their cost per ton is for the raw material - steel scrap [60]. Scrap therefore costs about $143/ton, which, incidentally, is within the range for market scrap prices in 1997. Therefore, subtracting materials costs, the product manufacturing costs for STLD are ≈ $132/ton. Next, a cross-sectional area of a *comparable* steel product is needed in order to calculate a cost per length of the product. Assume that STLD dedicated their entire 1.2 M tons of production to their thinnest cross-sectional-area sheet 0.04 in.x 40 in (1mm × 100 cm). One ton would equate to: 2000/((40)(.04)(.283 lb/in^3 for steel)) = 4416 inches of steel sheet, or 112 m. The manufacturing cost per unit length for this product would thus be $132/112 = $1.17/m.

To put this in perspective, if AMSC's cost of tape manufacture were only $1.17/m, then in 1996 it would have cost $0.14 M to manufacture their entire 120 km of tape for the year - or a mere 1.1% of total R&D and cost of revenue expenditures. This seems low considering tape manufacture is one of their main focus areas.

If STLD manufactured 9.5mm-diameter steel wire, this would cost $0.08 per meter. Consider that a thinner steel product may be manufactured simply by adding an extra set of rolls, so the marginal cost of a smaller-diameter product is small.

There are many arguments for and against thinking of steel production as a lowest-conceivable base-cost-of-manufacture analogy to HTS tape, and it is left entirely to the reader to consider the reasonableness of this argument. Table 9 presents the benchmarks discussed thus far.

TABLE 9 - Frame-of-Reference HTS Tape Processing Costs	Cost/m
Manufacturing cost of 3 mm steel wire: (HTS tape is typically 3 mm wide)	$0.008/m
AMSC scientists believe is achievable in long-term:	$0.08 -$0.44/m
Manufacturing cost of 9.5 mm steel wire:	$0.08/m
The silver cost of a typical HTS tape 3×0.25mm (f.f.=0.3):	$0.88/m
Manufacturing cost for Steel Dynamics thinnest product; (1mm×100 cm) sheet:	$1.17/m
An over-estimate - assumes AMSC devoted 100% of 1996 cost of revenue plus R&D to manufacture 120 km of tape. Also overestimates because it would include materials costs.	$105/m

4.4 Estimating the Total Cost

Table 10 presents the most reasonable estimate of tape cost based on a review of the literature. In table 10, CCPB is derived by assuming a J_c= 100kA/cm^2, which, while far above the best J_c values currently realizable even for short-length samples, it conveniently allows the reader to convert the result for any reported J_c.

TABLE 10 - Estimate of the Total HTS Tape Cost

Parameter	Value	Cost of HTS tape: \$/m	CCPB (\$/kAm) Assuming J_c= 100kA/cm^2 (assume F_R=1 & $\theta = 0^{\circ}$)
tape dimensions	0.25×3mm = 0.0075 cm^2	-	-
fill factor	0.3	-	-
final in-tape density of Bi-2223	4.5 g/cm^3 [28]	-	-
Ag market cost	\$5/troy oz = \$0.16/g	\$0.88/m	\$4/kAm
added, extra, cost of Ag for the OPIT Ag tube	\$7/troy oz = \$0.22/g [56]	\$1.2/m	\$5.3/kAm
cost of Bi-2223 powder	\$1 - \$1.2/g (mass-produced maybe \$0.2-\$0.3/g) [61]	\$1/m	\$4.4/kAm
tape manufacture cost, C_{man}	See table 9	\$0.44/m<<C_{man}<< \$105/m what seems reasonable?!	\$2/kAm<<$CCPB_{man.}$<< \$466/kAm
total		**\$3.1 + C_{man}**	**\$13.7/kAm + $CCPB_{man}$**

Figure 6 shows that 20kA/cm^2 would be a high J_c for a kilometer-length tape. From table 10, it would have a CCPB of \$13.7×(100/20) = \$68/kAm, not including cost of manufacture.

If the cost of manufacture is taken as \$10/m because it lies well to the low range of estimated tape manufacturing costs, then the CCPB would rise to \$290/kAm before profit.

Multiplied by the factor of 5.7 from section 4.2.1.5, and a CCPB of \$1653/kAm is realized.

In order for the tape to realize \$10/kAm for the above parameters would require J_c of 3318 kA/cm^2 (4740 kA/cm^2 for AC). However, table 4 shows that even the J_c of single-crystal Bi-2223 is only reported at ~ 1000 kA/cm^2- a good reference for the upper limit to J_c.

4.5 Competitiveness Based on the Cost of Silver

Because it is an indisputable cost, the *partial* materials-CCPB, based strictly on the market cost of silver will be considered. Referring to table 10 , a 20 kA/cm^2 tape gives a final CCPB of \$4/kAm × (100/20) × 5.7 = \$114/kAm for DC application. However, the entire installed cost of a copper DC cable is only \$59/kAm - about half the cost. So it seems the market cost of silver is more than enough by itself to disqualify HTS cables from competing with long-distance overhead DC transmission.

4.5.1 Optimistic Timeframe to Reach \$10/kAm

An empirically-based "rule-of-thumb" equation has been developed as an optimistic industry predictor of future values of J_c for short-length tapes. It is based on the extrapolation of past advances in J_c:

(eqn. 4.5.1-1) $J_c=9\times(\text{year}-1990)$ [62,63]

If the end-use cost of silver for a DC line is \$0.88×5.7 = \$5/m, then to realize \$10/kAm will require J_c of 220 kA/cm^2. Of course to realize this J_c for a one-kilometer tape requires a higher short-length value of J_c, but for simplicity we shall ignore this here. Equation 4.5.1-1 predicts this in the year 2014 (or 2025 for AC applications).

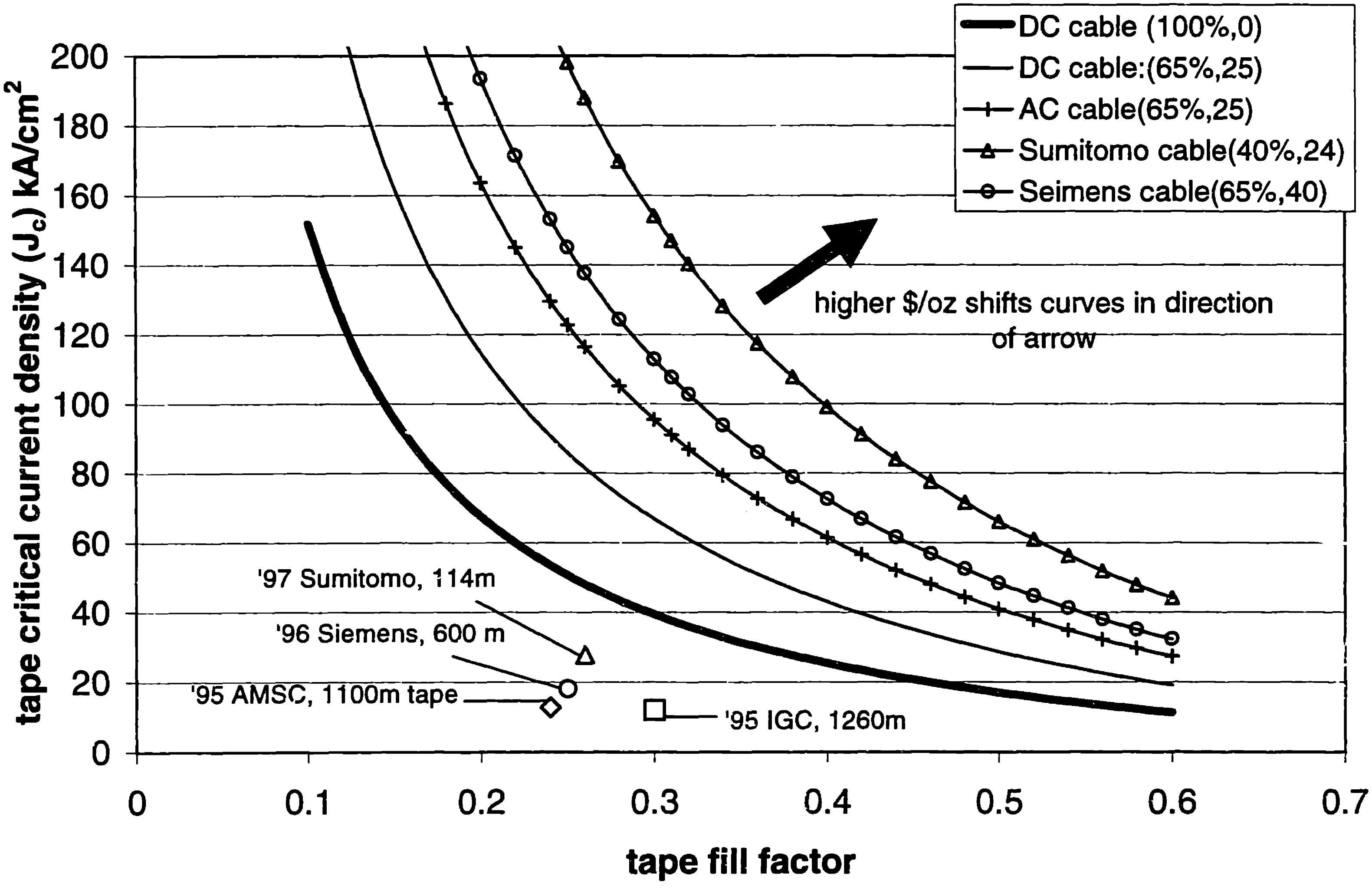
4.5.2 The Current Density/Fill Factor CPB Trade-off

Figure 11 illustrates the combinaton of f.f. & J_c which provide for a CCPB of \$10/kAm for different kinds of cables. It assumes silver is the only cost. The figure presents some current long-length tapes from some prominent manufactures and it is clear there is far to go to meet the \$10/kA criteria for a long-length sample, even for an ideal DC cable neglecting safety margin or profit considerations.

Figure 11 also illustrates how desirable it is to increase J_c and f.f. simultaneously. Unfortunately, as described in section 2.4.2, there is little technological scope for increasing f.f.

(Figure 11was plotted by substituting $C_{Ag,cable}$ =\$10 and C.M. = 1000 Am into equation 6.1-3)

Fig 11: Fill factor/current density needed to realize $10/kAm (silver cost only) As function of (% Retention,wrap angle) - $5/troy oz



4.6 Comparing Cable and Overhead Line Cost

Because HTS cable would be cable, not overhead transmission line, it is most obvious to compare HTS cable cost to standard cable costs, and then compare standard cable costs to equivalent overhead line cost. Table 11 makes the comparison*. The cost of DC cable is about 10 times the cost of a DC overhead line.

A separate comparison of the cost of overhead AC lines to AC cables of similar power rating showed cables costing from 7 times more for a 66 kV cable to 18 times more for a 400 kV cable [64].

It seems then that for HTS cable to be competitive on a capital cost basis with overhead DC lines, they must cost only a tenth that of an equivalent HVDC cable conductor.

The HTS cable will not require an oil cooling system, which may also entail environmental benefits. This cost saving must be greater than the cost of the liquid nitrogen cryogenic cooling stations which must dot along the length of the HTS cable. However, the HTS cable itself will be considerably more complicated from a manufacturing point of view - involving cooling channels, intricately wrapped HTS tapes, dielectric material, and a vacuum layer for low thermal heat in-leak.

*Note we are concerned in table 11 with the ratios between costs, not the absolute costs themselves as these would change with time. It is assumed the ratios would remain roughly constant.

TABLE 11 - Direct Current Transmission Line Costs

Source:Federal Power Commission *Report on Underground Power Transmission*, April 1966.

Range of Estimated Costs per Mile for HVDC Overhead Transmission Lines (1965)							
Operating Voltage (kV)	ACSR Cond. Size (MCM)	Nominal Summer Thermal Rating (MVA)	Reported Range of Material Cost/Mile $1000 [a]	Foundations [b] $1000/mile	Tower Erection and Stringing [c] $1000/mile	Reported Range of Right-of-Way $1000/mile	Adjusted Average Total Cost/Mile $1000
± 600	2-1590	2160	43.2-62.6	5.9-34.0	27.7-60.0	13.0-47.5	129.0
% of total line cost			**33%-48%** **avg: 40%**	4.6%-26%	21%-46%	10%-37%	
Est. Costs for HVDC Underground Transmission with Pipe-Type High Pressure Oil-Filled Cable (1965)							
			Material Cost/Mile $1000 [d]	Fixed terminal cost[d]	Installation cost[f]		
± 600	2-1590	2160	771-795	156-502	175-800	-	1185-1341
Multiple of cost of equivalent overhead line			x12-18				x10
a: Includes structure, insulators, conductors, fittings, and all other materials including foundation material.							
b: Includes all foundation installation, surveying, grounding, and any necessary construction roads.							
c: Includes all costs of assembling the material into a complete line							
d: Includes pipe, cable, manholes, oil and joining material, sales tax and stores and handling charges.							
e: Includes labor and material for two terminals consisting of single conductor potheads and structure, cable from trifurcator to pothead, one oil pressurizing plant and cathodic protection.							
f: Includes all labor costs for installing pipe and cable, making joints and oil filling. The second circuit is assumed to be in the same trench but no other circuits within 15 ft.							

4.7 The "Conductor-Only" CPB in Perspective

Table 11 presents that the materials cost for a 600 kV, 2160 MVA DC overhead line represents approximately 40% of the total line cost. The cost of the copper used in the line, at the 1965 price of $0.5/lb is $25,000/mile, or 19% of the total line cost, which is in agreement with section 4.2.

An important observation is to note that the cost of copper metal is a far lower fraction of the total cost of a HVDC *cable* than for a HVDC *overhead* transmission line. The cost of copper represents only about 2 % of total cost of a HVDC cable, whereas it is about 19% for an overhead line. Considering their far-higher CCPB, this suggests the HTS cable would have a relatively better chance of competing as against a HVDC underground cable.

Chapter 5
Direct Current Transmission

5.1 Suitability of HTS Cable for DC Transmission

The groundwork has now been laid to understand why a HTS cable would be more competitive operating in DC rather than AC. Chapter 3, figure 8 in particular, make clear that DC cables are more economic in terms of HTS tape costs.

DC HTS cables have no AC loss problem, and could therefore be operated much closer to their I_c, which offers a great advantage in terms of HTS tape cost. The dielectric breakdown strength of dielectric insulating materials is greater in DC than in AC, making cable design simpler, and permitting higher-voltage operation. For these reasons, it is believed a HTS DC cable may be able to transport up to 3 times the power of a similar AC cable [65].

With its lower losses, a DC HTS cable could have wider cooling-station spacing, and hence lower cryogenic cooling station capital cost per km than a comparable AC cable.

5.2 Overview of DC Power Transmission

The vast majority of electric power transmission in the world today is AC. This is because it is easier for generating stations to generate AC current, because nearly all utilization of power is AC, and because transformers make it a simple matter to adjust the voltage/current level through power lines. However, standard HVDC transmission has many clear advantages over AC:

a)
DC lines are ideally suited for transmitting large amounts of power over long distances. The power carrying capacity of AC lines is limited by stability issues for long distances ie, the ability to maintain all machines at both end of the transmission line in synch.

Reactive compensation of DC lines occurs only at the AC side of the AC/DC conversion stations, the amount of-which is *independent* of the length of the line. Beyond about 400 km, DC lines therefore require less reactive power than AC lines since the reactive power of an AC line continues to increase with distance.

b)
DC lines can transmit greater power with lower losses. Power transmitted by overhead cables can be increased to 147% of AC lines, with 68% of the losses of an AC system. For cables DC may transmit 294% more power with 34% of the losses [66].
c)
The power flow through a DC line may be easily controlled.

d)
A DC line can provide for the transfer of power between separate AC transmission grids without requiring that they operate at the same AC frequency in synch.

e)
Underground, and especially under-sea AC cables suffer stability and cost problems which make them both technically and economically impractical beyond a short distance. DC lines are free from the technical problems which make AC impractical. There is no limitation to undersea DC transmission.

f)
Less dielectric insulation is required; cooling of underground cables is improved as a result. DC cables can transfer higher voltages. No sheath-current induction losses.

g)
Installed cost per unit line length of a DC line is lower. The right of way is narrower, transmission tower size may be less because the conductors may be closer together, conductor costs are lower and only 2 conductors, instead of 3 for an AC line, are needed, and the weight per mile of conductor may be less.

DC lines are therefore used for the following applications:

1) Long distance bulk power transmission.
2) Underground or undersea cables - AC submarine cable becomes impractical after between 24 and 48 km [67].
3) "Back-to-Back" stations. Connecting two separate AC systems to facilitate power exchanges between them without the complication of requiring they operate at in synch at the same frequency - this application may even invoked for zero transmission distance.

DC transmission requires that the current be converted from AC to DC at the input end, and from DC back to AC at output. The equipment required to accomplish this is extremely expensive and explains why use of DC transmission is not widespread. Technical developments which reduce the conversion cost would certainly lead to greater use of DC transmission. Technological advance is ongoing in this area. The first commercial DC line (Sweden-Gotland 1954) used the "mercury arc" valve for conversion. Solid-state electronics gave rise to the thyristor (silicon controlled rectifier) in the late 1950's, and by the mid 1970's this was the only technology seriously considered for new DC lines. The most recent technology, which some companies are now attempting to commercialize is DC "Light" based on voltage source converters. It is too soon to say how, or whether this technology could affect the economics of DC transmission.

Because of the greater initial capital cost, but lower transmission cost, at some transmission distance the DC line becomes competitive. For overhead lines the distance is 500-800 km, for undersea cables 24-48 km, and for underground cables 50 - 100 km.

In 1964 Gerber identified the fundamental technical conflict which continues today to underlie the competitiveness between AC and DC transmission when he surmised; the basic problem of AC transmission is that of inductive and capacitive reactance; the basic problem of DC transmission is switching.

5.3 Potential for Reducing AC/DC Conversion Costs

A HTS DC cable, were it able to transmit the same power at higher current, could provide for the design of AC/DC conversion stations cost-optimized with respect to current and voltage: J. Arrillaga, an early expert in the field writes:

"The power handing capacity of a thyristor increases with increasing current. ...
However, in two-terminal transmission schemes, the rated voltage and current values are mainly determined by the transmission line, which means it may often not be possible to fully utilize the capacity of modern large thyristors.

In a back-to-back link...it is possible to utilize the thyristors optimally, which means a high current and low voltage. This will minimize the number of thyristors, and thereby also the valve cost. Other voltage-dependent costs will also be reduced, for instance those of the building and the transformers. " [66]

Placing the magnitude of potential savings in perspective, thyristors represent about 35% of the cost of conversion equipment, the convertor transformer about 25% [66].

At least one DC HTS cable paper recognized the potential savings when they wrote:

"A superconducting DC cable can provide lower transmission costs compared to a conventional cable solution, carrying more power at lower voltages, greatly simplifying AC-DC conversion." [68]

It must be remembered that transporting the same power at a higher current level will increase the kA-km of cable required *per unit* of power transported. This is precisely why higher cross-sectional-area copper lines are not used for high-current transport on DC lines – the thyristor cost savings don't justify the added copper cost over the whole length of the line. The first observation then is that lower-voltage/higher-current DC power transfer makes more sense over shorter distance where the extra conductor cost is negligible.

Even if fixed costs for a HTS cable are virtually independent of current capacity, this does not make the marginal cost of installed current capacity free: a larger quantity of HTS tape would be needed, which is presently costs far in excess of the $10/kAm of copper.

Chapter 6
Market Limits

The advantages of HTS DC transmission have not been entirely ignored. In one proposal, exceptional in its bold, visionary look forward, the author conceptually designed a 10,000 km DC HTS cable foreseen to link major cities such as Tokyo, New York, and Paris together with major hydroelectric projects in remote parts of Siberia and Canada [65].

How much silver metal would a single 10,000 km stretch of such cable consume? Each cable is meant to conduct 40,000 A of current, using tapes 10×0.2 mm with J_c of 10 kA/cm^2 and f.f. of 0.35. Assuming the tapes retain 100% of their J_c when incorporated into the cable (F_R=1), (which they won't) then each tape will conduct 70 A and 571 tapes will be needed. Assume now that the tapes would be laid straight, flat along the cylindrical former – so only 1 m of tape is needed per meter of cable distance. A single 10,000 km cable would then require 571 tapes×10,000,000 m × 1.3 cm^3 Ag/m of tape = 7.4×10^9 cm^3 , or, × 10.5 g Ag./cm^3 = 7.8×10^{10} g of silver.

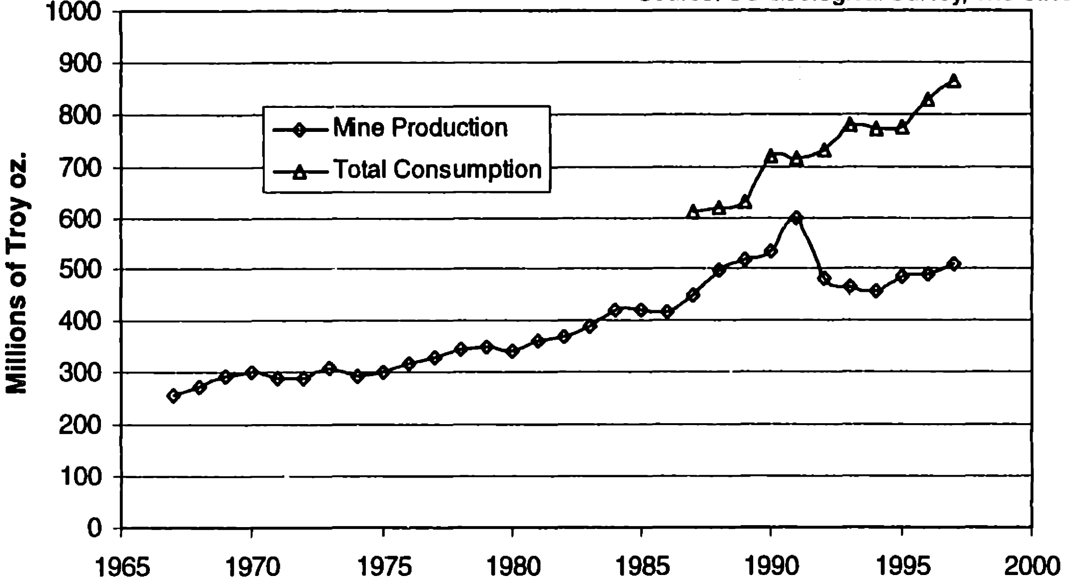
For the two parallel cables envisioned for a single 10,000 km link, this works out to 5000 million troy ounces of silver. This is as much silver as was mined in the entire world for the ten years from 1988 to 1997 inclusive. One might then expect such a project to affect the price of silver, rendering it rather less and less economically viable as the cable is produced and the price of silver skyrockets.

This simple analysis brings to the fore the danger that HTS cable could conceivably become a victim of its own success - driving up world silver prices to the point where any prior economic advantage of the HTS cable is lost. The problem would be aggravated by savvy market players who would hoard the metal. The hard-fought technical gains which initially made the HTS cable economically viable would be vitiated by their own success. While evaluating the specter of silver shortages may seem premature today, the seriousness of their eventuality, coupled with the potential that today's research dollars could prove one day wasted, suggest the issue deserves at least a look.

How large a HTS cable market can the world silver market support? A detailed microeconomic analysis of the elasticity of supply and demand for silver is beyond the scope of this thesis. Common sense shall be resorted to instead. It seems reasonable to expect that as a substantial new, continuous yearly silver demand begins to approach the yearly mine production of silver, the long-term price would increase tremendously.

Figure 12 shows that silver consumption has been significantly higher than mine production for the past 10 years. This is possible because of de-stocking of investment reserves and the recycling of previously consumed silver. A demand of 10, 20 or even 40% of mine production would be on the same order as some other industrial applications like the photography industry which consumed 232 M troy ounces in 1997. However, the HTS cable market could not, in the long run, consume more silver than mine production generates. This is because the recycling rate of silver consumed by HTS cable would, or at least had very well better, be extremely low since transmission line applications have lifetimes expected to span decades, and the silver could not re-enter the market prior to retirement of the line.

Fig. 12: World Silver Consumption and Mine Production



Source: US Geological Survey, The Silver Institute

6.1 Silver Consumption of a Hypothetical HTS Cable Market

How large a HTS cable market would consume one year of mine production , or ~ 500 M troy ounces of silver per year?

The total silver consumed by an actual HTS transmission line would depend on the following grouping of variables:

Tape parameters:

- $J_{c,1m}$.& C_{LDJ}
- f.f.

Cable parameters:

- F_R
- tape wrap angle
- for AC cables the average anticipated operating value of (i), the ratio of peak current to I_c is critical. Higher (i) will require less use of HTS tape, but will result in far higher AC losses.
- The use of a magnetic-field shielding layer will increase the total tape consumed. This is tape is not accounted for by the operating current requirements of the cable.

Transmission line parameters:
- the average length of the HTS cable- (J_c decreases with length)
- # of parallel cables for the line (usually 2 for DC & 3 for AC)
- safety operating margin

TABLE 12 - Typical values of parameters determining the silver consumed in a HTS cable

Parameter	Typical value	Typical Range of values
J_c, kA/cm^2	15 for 1 km length	4 to 17 @ 1 km; 20 to 70 @ 10 cm.
f.f.	0.3	0.1-0.35
F_R	0.65	0.33-0.65
wrap angle (degrees)	25°	15°-40°
# of parallel cables/transmission system.	2	1-3

C.M. is the size of the cable market in Ampere-meters.

(eqn. 6.1-1) $$(C.M.) = I_{c,cable} L_{cable}$$

(eqn 6.1-2) $$M_{Ag,cable} = \left(\frac{1}{\cos\theta}\right)100\times A_{tape}(1-f.f.)\rho_{Ag} N_{tapes} L_{cable}$$

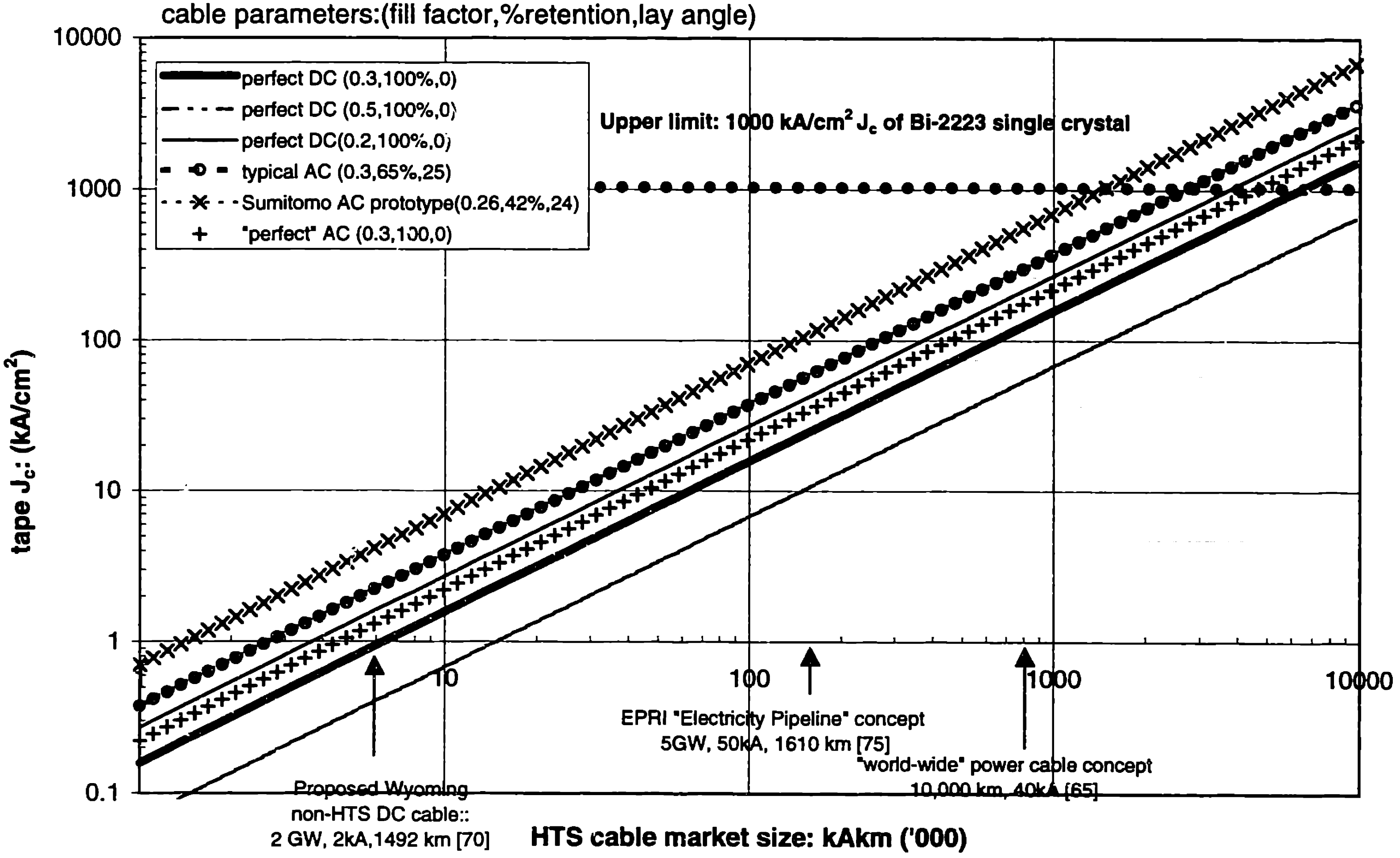
Equation 6.1-2 provides the mass of Ag consumed, in grams.

Manipulating equations 6.1-1, 6.1-2, 3.2.1-1, and 4.2.1.1-5 and multiplying by P_{Ag} yields an expression for the cost of silver for a given cable market size (CM) in A·m. Of course dividing equation 6.1-3 by P_{Ag} gives the mass of silver required for a given C.M. Operating margin, profit margin and AC cable adjustment may be made simply by multiplying by the appropriate factor.

(eqn. 6.1-3) $$C_{Ag,cable} = \frac{100}{31.1}\frac{P_{Ag}\times\rho_{Ag}\times C.M.\times(1-f.f.)}{(f.f.\times F_R\times\cos\theta\times J_c)}$$

Figure 13 illustrates the size of an HTS cable market which would consume "only" one mine-year of production for a given tape J_c. Note a fundamental upper limit is for J_c = 1000 kA/cm^2, which would certainly be unrealizable by the OPIT process.

Fig. 13: Limits to the Size of a hypothetical HTS Cable Market: For a given tape current density, shows the size of HTS cable market which would consume 1 year of world silver production (500 M troy oz silver)



Chapter 7
Transmission Losses

7.1 Cryogenic Cooling Efficiency

It is commonly believed that the primary advantage of HTS is their abiltiy to conduct electricity with no power loss. In fact power must always be supplied to operate the lines.

Power losses from the HTS cable become the load for the refrigeration system. Power must be supplied at room temperature to remove the heat generated by the cable at a lower temperature, thereby maintaining the HTS at the lower operating temperature. The power required is given by the Carnot relationship:

(eqn. 7.1-1)
$$\frac{P_{300K}}{Q_{Top}} = \frac{1}{K_2}\frac{(300-T_{op})}{T_{op}} = P.R.$$

T_{op} is the operating temperature of the HTS. K_2 is the coefficient of performance, which is about 0.25 for large transmission line refrigerators [69].
The power ratio, PR, is the key result - it is the power consumed at room temperature to extract a watt of heat generated at the cryogenic temperature. At 77 K PR is ~ 11 W/W, whereas about 205 W are required to extract 1 W at 7 K.

For AC cables, a trade-off will exist in determining the power-consumption-minimizing temperature. On the one hand a lower T_{op} will reduce T/Tc, and therefore increase Ic, thereby lowering the AC losses for the same power rating. This is countered by the greater power consumed in removing those losses, as per equation 7.1-1. A rule-of-thumb is that $0.6T_c$ is the T_{op} which minimizes total power consumption for AC operation [69]. This suggests Bi-2223, with a T_c of 108K, would be optimally operated T of 65 K for AC operation.

T_{op} for DC cables would depend on a trade-off between greater losses and the value conferred by higher I_c in terms of being able to transmit greater current.

7.2 Copper and Aluminum Cryo-Cooled Cables

Resistivity of copper and aluminum drops dramatically at cryogen temperatures. They experience no AC hysteresis losses. Is it then possible to simply cool standard copper or aluminum to cryogen temperatures and would this be competitive with HTS cable? From a loss perspective, the only advantage exists if, for the same total losses, the cryo-cooled material could transmit greater current density.

(eqn. 7.2-1) $Q_{rt} = I_{rt}^2 R_{rt}$
(eqn. 7.2-2) $Q_T = I^2 R_T$
(eqn. 7.2-3) $R_T = \rho_T / A$

The total power losses must be equal. To make the total loss equal, we equate the two as per the

(eqn. 7.2-4) $Q_{rt} = (PR) Q_T$

The ratio of the current density carried at cryogenic temperatures to that at room temperature, with each giving the same total resistance loss, is the key figure of merit. This ratio must be > 1 for there to be any advantage, in terms of losses to a cryogenic cable.

(eqn. 7.2-5) $$\frac{I_T}{I_{rt}} = \sqrt{\left(\frac{\rho_{rt}}{\rho_T}\left(\frac{1}{PR}\right)\right)}$$

TABLE 13 - Loss Advantage of Cryo-Cooled Copper and Aluminum

Temp., K	Resistivity, ohm-m		Estimated COP [69]	PR - Watts consumed per Watt removed	Ratio of current carried at cryo-T to current at room-T yielding same total power loss.	
	Copper	Aluminum			Copper	Aluminum
10	.002	.000193	.202	143	2.45	9.9
20	.0028	.000755	.211	66	3	7.4
40	.0239	.0181	.228	28	1.6	2.3
60	.097	.096	.245	16	1	1.3
80	.215	.245	.262	10	.87	1
100	.348	.442	.26	7.7	.8	.9
150	.7	1.006	.26	3.8	.8	.84
200	1.04	1.587	.26	1.9	.92	.94
300	1.72	2.733	-	-	-	

Figure 14 demonstrates that only below 60K does this scheme begin to become interesting, and only really interesting for aluminum at 10 K. Despite the 10-fold advantage of an aluminum conductor at 10 K, it is apparently not yet enough as no transmission lines use such a scheme. The reason must lie in the fact that this analysis has ignored other thermal load such as heat in-leak and the viscous friction of the cooling medium. The added thermal load, complexity and cost of cryogenic equipment do not make up for the 10-fold current density advantage offered by aluminum based on thermal dissipation only.

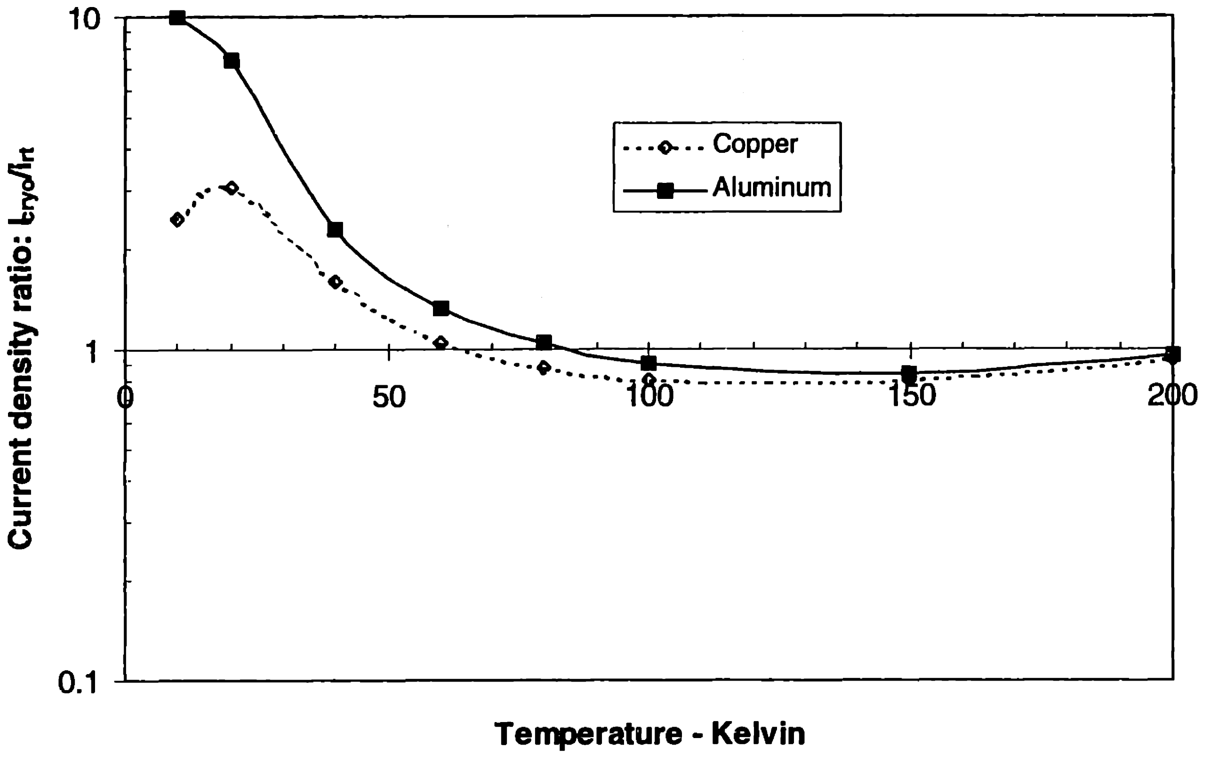


Fig. 14: Current Density Advantage of Cryocooled Copper and Aluminum

7.3 The Loss Supply Disadvantage of HTS Cables

The losses incurred by a HTS cable will always have a higher "effective" cost than the losses of a standard transmission system. In a standard line, transmission losses are supplied at the generating station at the MCG. However, the power supplied (the losses) to the cyrogenic cooling stations which service the HTS cable are distributed along the length of the line. At the very least some power would be lost in transmission to the cooling stations. At worst, power would need to be purchased from other utilities, which could twice or more the MCG.

(eqn. 7.3-1) The cost of energy supplied to cooling stations = (LSD)(MCG)

LSD is the "loss supply disadvantage" which standard transmission lines enjoy over HTS cable. The following probably represents reasonable bounds:

(eqn. 7.3-2) $1 < \text{LSD} < (\text{market cost}/\text{MCG})$

7.4 Investment Value of Eliminating Transmission Losses

How much would a utility be willing to invest today to eliminate transmission losses? What premium, in percentage terms, is it worth paying for a HVDC transmission line having lower losses? The answer is crucial to determining how much more one would be willing to pay, on the basis of loss reduction, to install a HTS cable as compared to a standard cable. In short, how strong is the motivation to reduce losses in HVDC? There are four obvious kinds of value realizable by reducing transmission losses.

1) The utility no longer needs to generate power for-which there are no sales. These saved losses are valued at what it would have cost the utility to generate them - the marginal cost of generation (MCG.) The present value of this "stream" of cost savings is the **lower-limit** investment value of saved losses.

2) Lower total transmission capacity is needed in order to deliver the same amount of power.

3) Lower generation capacity need be installed to deliver the same quantity of power. Reducing losses for an existing facility is like adding generation capacity.

4) For a DC line, assuming the same delivered power, less power need be converted from AC to DC at the generation source, thereby allowing a lower capital investment for conversion equipment.

A detailed calculation of 2, 3 and 4 may be avoided by considering that saved losses could conceivably be sold. The present value of "sold" losses, minus the cost of their generation, is the maximum **upper limit** to the investment value of saved losses. The average selling price for investor-owned utilities in the US is here taken as 7.2 ¢/kWhr [70].

7.4.1 Analytical Framework

The following shall establish the criteria which HTS cable must meet in order to be competitive on the basis of losses with a standard base-case copper or aluminum transmission line.

TC_{bc} = the transmission capacity of the base case line.
Q_{bc} = Transmission loss of the base case line in W/length.
MCG = the marginal cost of generation
TLC= Transmission line cost.
LSA = loss supply advantage enjoyed by as standard transmission line.
LF = load factor of the transmission line.

(eqn. 7.4-1) $$f_{bc} = \frac{Q_{bc}}{LF \times TC_{bc}}$$

This is the fraction of transmitted power lost per unit length, per unit power transmitted.

<u>In order for HTS cable to be competitive on the basis of losses with standard conductors, the following relation must hold:</u>

(eqn. 7.4-2) $$\mathbf{f_{bc} > (LSD)f_{hts}}$$

For HTS cables:

(eqn. 7.4-3) $$f_{hts} = \frac{PR \times Q_{hts,total}}{TC_{hts}}$$

The present value (PV) of the saved generating losses at the marginal cost of generation, and the PV of the losses sold at the market rate must be calculated over the assumed life of the transmission line. Project life-time and discount-rate (dr) are the critical parameters for a PV calculation. The discount rate must be at least equal to the base standard rate of the internal investment return expected by the utility for projects of similar risk.

In 1997 Southern Corporation, a large U.S. utility generated \$3.2 B gross profit on assets of \$35.2 B which gives a return of 9%. For Texas Utilities it was 9.6% in 1997, Carolina Light and Power 11%. The rates are similar for the past few years. It seems safe to assume then that *greater than* a 10 % return would be needed on capital invested to save transmission losses. In fact, because HTS cable is a new, untried technology, one would expect the discount rate to be adjusted upward significantly for such an endeavor as compared to investments based on known technology. Uncertainty must always command a premium.

(eqn. 7.4-4) $$SL = 8760 \times LF \times TC_b \times (f_{bc} - (LSA)f_{hts})$$

(eqn. 7.4-5)

$$PV_{SavedL} = SL \times MCG_y \times \sum_{y=1}^{y=lifetime} \frac{1}{\left(1 + {dr}/{100}\right)^y}$$

(eqn. 7.4-6)

$$PV_{SoldL} = SL \times MPE \times \sum_{y=1}^{y=lifetime} \frac{1}{\left(1 + {dr}/{100}\right)^y}$$

MPE = market price of electricity is taken here as 7.2 ¢/kWhr

(eqn. 7.4-7)

$$\mathbf{PV_{savedL} < \text{investment value of eliminating transmission losses} < (PV_{soldL} - PV_{savedL})}$$

The premium one would be willing to pay for a HTS cable above a standard HVDC line, based on eliminating its losses, is what we would like to know. This is realized simply by dividing equation 7.4-7 by the cost of the transmission line.

7.4.2 Case: The Proposed Wyoming-San Francisco HVDC Link

In order to have a frame-of-reference for the motivation to reduce losses, the above analysis must be applied to a real-life case. Because it has already been determined that HTS cable is more suited for DC transmission, a DC transmission case would be an appropriate comparison. In 1996, the Wyoming Science, Technology and Energy Authority funded a detailed study of the potential to export cheap Wyoming power via DC transmission, to market in California or Texas [71]. The cost parameters from that study which are salient to the present analysis are presented in table 13.

For this base case, one would be willing to pay at most 76% more for a zero-loss transmission line.

TABLE 14 - Wyoming HVDC Case: Calculating the Value of Transmission Losses	
Transmission capacity TC_b	2000 MW
DC voltage	500 kV
Load factor LF	0.85
Transmission length	927 miles (1492 km)
fractional loss per mile f_b	0.00004
total fractional loss of transmission	0.03708
total fractional loss per mile assumed for the HTS cable f_{hts}	0
Heat generated per meter of transmission line	42 W/m
f_{bc}	21 W/GWm
Total transmission-line cost performance measure:	$59/kAm
Marginal Cost of Generation MCG	$8/MWhr
Assumed average selling price of power<doe>	$72/MWhr
Total DC line cost	$352 M
Total AC-to-DC-to-AC conversion costs	$320 M
Total technical services (surveying, mapping, engineering, construction management)	$29.84 M
Total right of way (easements and damages)	$ 8.35 M
Total transmission project cost	$718 M
Total generation construction cost	$2000 M
Operation and Maintenance cost	$7 M/year
Project discount rate (dr)	13.23%
Project lifetime	35 years
Total transmission losses	552,195 MW-hrs/year
Discount factor	7.57
Present value of losses saved (PV_{SavedL})	**$33 M**
Present value of losses sold minus (PV_{SavedL})	**$267 M**
Maximum premium one would pay for a zero-loss HTS cable: $33/$352 to $267/$352	**9.5% to 76%**

7.4.2.1 The Total-Cost-of-Transmission Performance Measure Benchmark

Transmission line cost for the Wyoming project was $352/2000MW/927 miles = $190/MW-mile ($118/MWkm) installed DC transmission capacity. For a 2000MW/500kV = 4000 A (2 lines carry 2000 A each) current, the DC line costs a total of **$59/kAm** – this includes all costs of materials, cable and installation.

7.4.2.2 Competitive Loss Level of HTS Cables

The proposed 2 GW Wyoming HVDC line had losses of 42 W/m, or f_{bc} = 21 W/m/GW. To be competitive on a loss basis with a HVDC overhead line, the HTS cable must therefore experience losses such that

(eqn. 7.4.2.2-1)
$$Q_{tot} < \frac{TC_{hts} \times f_{bc}}{PR \times LSD}$$

At 77 K, PR ~ 11 W (assume LSD=1). A 2 GW HTS cable must therefore have $Q_{tot} < 3.8$ W/m to be competitive with the Wyoming case.

1-2 W/m of heat in-leak is a benchmark often seen in the literature [72,73]. 1 W/m is also an AC loss target for AC cables. A prototype HTS AC cable by Seimens realizing 0.9 W/m was considered "a record" [38].

In part, this explains why HTS DC cables have been previously assessed as suitable only for very high power transmission [2]. The losses of a DC HTS cable are largely the same whether the cable transmits 100 W or 100 GW, but the fractional loss becomes smaller as transmitted power increases.

The competitive transmission capacity, on a loss basis, of a HTS cable, is therefore extremely sensitive to the amount of heat must be removed per-meter of HTS cable by the refrigeration system.

7.5 Surety of Loss Savings with HTS Cable

A consensus regarding the potential for HTS cable to reduce losses has not been realized in the research community. As E.B.Forsyth of Brookhaven National Laboratory put it:

"*Perhaps it is fitting to round off a discussion of losses by debunking a prevalent myth that superconducting systems are 'lossless' and that this feature is the main appeal of these systems. Such is not the case. In numerous studies it has been shown that the losses of superconducting designs are comparable to conventional transmission methods when the systems are optimized for lowest lifetime cost.*"[74]

Chapter 8
Cryogenic Cooling

8.1 Supplying Cooling Stations with Electricity

Cooling stations need to be located periodically, along the length of a HTS DC transmission cable. Perhaps they might draw their power directly from the HTS transmission cable they are cooling. However this would be akin to supplying an apartment complex directly from a high-voltage transmission line. A complicated splice would need to be introduced to the HTS cable, and transformers or other expensive intermediary electrical conversion equipment would be required in order to supply the cooling station. If tapping the HTS line is difficult for AC transmission lines, it would be far more expensive for DC lines because of the AC-DC conversion necessary:

"*Power electronic converter and inverter systems are expensive, thus intermediate tap-offs into a HVDC line for local use becomes impractical.*" [71]

However, a consensus apparently does not exist in all quarters regarding the feasibility of such a tap-off. A conceptual design of a HTS DC cable by the EPRI proposed:

"*...incremental cooling stations every 10km. To maintain vacuum, pumping stations would operate every kilometer. These stations would be powered by taps off the dc line every 100 km...*" [75].

Another possibility is for cooling stations to be supplied by the existing transmission network. However, if the HTS cable traverses remote areas then feeder transmission lines would need to be constructed exclusively to supply the cooling stations. Depending on the power requirements of the cooling stations this could become costly.

8.2 HTS Cable Reliability

Reliability is a hallmark of the electric utility industry.

The operation of a HTS cable can only be as reliable as that of its refrigeration and pumping system.

8.2.1 Potential for Self-Reinforcing, and Cascading Failure of HTS Cables

If the reliability of the refrigeration & pumping system is dependent upon electricity supplied by the net, this adds a further reliability risk, beyond mechanical failure, in the event of local disruption to the power supply or a blackout. Creating a transmission system whose successful operation depends on transmission opens the possibility of a self-reinforcing power outage. For example, should any of the power consumed by the cooling stations depend on the very power transmitted by the HTS cable, then a failure of one cooling station, could cut the line, thereby cutting power to all the other cooling stations.

If the power transmitted by one HTS cable supplies the cooling stations of other HTS cables, then a cascading kind of failure is conceivable whereby an outage of one HTS cable cuts power to the cooling stations of others, which, in turn, cause failure of those HTS cables, etc etc.

It appears then that cooling stations would need to have emergency generators, or reserve supplies of liquid nitrogen installed.

Cooling System Redundancy

Backup generators do not protect from mechanical breakdown or maintenance. The cooling stations and cable would therefore likely need to be designed such that any cooling station could be bypassed altogether in the event of its failure. Such redundancy would more than double the capital cost of refrigeration because, for a given cable cooling channel radius, it would:

a) more than double the number of cooling stations required per unit line length.
b) require that each station have more than twice the installed pumping and heat removal capacity than required for every-day operation.

8.3 Cable Vacuum Requirement for Low Heat Leak

The steady-state heat-flux equation for a cylinder is given as follows:

(eqn. 8.3-1)
$$Q_{cond} = \frac{2\pi k(T_o - T_{cooling})}{\ln\left({R_o}/{R_i} \right)} \text{ W/m}$$

Assuming an operating temperature of 77 K ,(T_o-$T_{cooling}$)= (300-77) = 223K.

Asbestos is an excellent thermal insulator with $k_{77K} \cong 0.074$ W/m/K. A very low heat-leak of 1 W/m of cable is viewed as desirabe for HTS cables. With asbestos insulation, this would require $R_o/R_i = 1\times10^{45}$- an impossibly large tube. The only way to realize such low thermal heat leak is by lowering k. The only means of realizing sufficiently low k is through introduction of a vacuum. Therefore, a HTS cable would also require a vacuum annulus in order to maintain 1 W/m of thermal heat-leak.

"*Liquid-nitrogen –cooled systems will pump by cryosorption.*
...Although in theory a liquid-nitrogen system can produce a low heat in-leak, and thus a low room-temperature compressor load, it will require great care in practice to engineer a system which can meet this goal." [74]

8.4 Cooling Load

On a per-meter basis, the sources of heat to be removed are as follows.

(eqn. 8.4-2) $Q_{tot} = TL + Q_{flow\ friction}$ W/m

(eqn. 8.4-3) $TL = Q_{heat\ leak} + Q_{AC\ losses} + Q_{miscellaneous}$ W/m

TL = the "thermal load" the liquid N_2 must remove per meter in *addition* to its own viscous self-heating, which can be significant.

Chapter 9
Miscellaneous

9.1 Vandalism

"In urban areas, vandalism involving damage to overhead structures is becoming more common. This usually takes the form of tower climbing, stone throwing at equipment, and rifle or pistol shooting at the insulators." [76]

A novel form of vandalism which would take advantage of the unique materials properties of Bi-2223 would be to affix a powerful hand-held magnet to the outside of the cable. Section 2.4.1 describes the magnetic properties of Bi-2223 in greater detail.

9.2 Right-of-Way

It is generally believed that the right of way required for a HTS DC cable would be smaller than for traditional DC lines. A co-axial HTS cable would essentially be a pipeline, and would therefore require less right-of-way width. This could undoubtedly reduce the right-of-way cost to some extent. However, it is undoubtedly the case that a significant fraction of the cost of right-of-way is a function of the number of different land-owners and political entities the utility must deal with per unit length of transmission line. Due process relating to these concerned groups must occur regardless of the width of the sliver of land required.

The placement of cooling stations could add to the right of way. Both the stations themselves, and the transmission lines which must be built to connect them to the grid would require right-of-way.

9.3 Deregulation of the Electric Power Industry

The prospect of deregulation has been greatly anticipated for a long time. The premise behind deregulation is that market-players compete with one another, committing to investments strictly on the basis of their market competitiveness. If this is the fundamental characterization of deregulation, then it says nothing whatsoever about whether a HTS cable *would* be competitive with standard cables, which has been the topic of this thesis. It only says that they *must* be.

De-regulation could bring about the demand for more, and more varied transmission schemes. If a scheme for-which HTS cable is competitive exists, then deregulation should help bring such situations to the fore in the name of profit.

The most obvious transmission scheme for-which HTS cable might be competitive is one where a very high value is placed on the space or weight savings offered by a HTS cable.

Chapter 10
Conclusions

a)
HTS may be far more efficiently used for direct-current transmission than alternating current.

b)
HTS cable capable of eliminating all losses was found to be worth a premium of anywhere from 9.5% to 76% more than an overhead HVDC line. However, it is not at all clear that a DC HTS cable would in fact have a low-loss advantage over standard HVDC transmission lines, except, perhaps, for very large transmission capacity on the order of Gigawatts. Losses are already low, the potential savings realizable are not clear, and even in a best-case scenario they are not compelling-enough financially in their own right to warrrant the greater reliability risk, technical complexity, and vulnerability entailed by a major HTS cable. For HTS cables to be compelling they must also confer a *clear and significant* capital cost advantage.

c)
Silver is indispensable and will remain indispensable to HTS tape manufacture for many reasons.

d)
HTS cables are not competitive on a capital cost basis with standard overhead HVDC transmission lines. It is doubtful whether they would be for underground HVDC cables. It is unlikely they will realize competitiveness in the near future because of conclusions (e) and (f) below.

In thinking about the capital costs of HTS cables it is important to distinguish between i) the cost of the HTS tape, which is the conductor, ii) the fabrication cost of the HTS cable, and iii) the installation cost of the HTS cable.

At the present J_c level of kilometer-scale HTS tape, the cost of HTS based only on the market cost of the silver metal used in the tape is nearly the same, on a dollar-per-kA·m basis, as the total final installation cost of a standard HVDC overhead line. Furthermore, the cost of silver represents a minority fraction of the total cost of the HTS tape since silver processing costs and the cost of the Bi-2223 powder are also significant. In addition to materials costs, it was demonstrated that the manufacturing cost of HTS tape is most probably several times more expensive than all materials costs combined.

The total cost of HTS tape has its analog in the cost of copper overhead transmission line. However, HTS tape must be incorporated into a HTS cable, and this will also add significantly to the total cost.

The cost of standard underground HVDC cable is about ten times that of the equivalent overhead line. HTS cables would therefore have a better *chance* of being competitive with HVDC underground cables since the cost of the HTS tape conductor by itself would constitute a lesser fraction of the total all-inclusive cost of the HVDC cable.

A HTS cable would be significantly more technically complex than a standard underground HVDC cable. One cost savings of a HTS cable is that it would not need an oil cooling system as standard cable does. However, it would need cryogenic cooling plants at intervals along its length.

e)

The silver capital cost of HTS tape is primarily dependent on the tape J_c and fill factor. It seems extremely unlikely that the fill-factor of HTS tapes may be increased from present levels of around 0.3 except at the expense of J_c.

Potential does exist for increasing tape J_c. However, the J_c of HTS tape declines significantly with tape length and this is one of the greatest technical problems faced by HTS tapes. The tape cost on a \$/kAm basis would therefore increase with application length, making them progressively less competitive for long-distance applications.

This thesis also presented evidence suggesting that tapes having higher J_c experience more rapid degradation of their J_c with length. If this is the case it would greatly increase the J_c levels which need to be realized in order to provide for economical long-distance applications. However, the evidence for this was not conclusive, and requires a detailed scientific study. This report recommends such a study.

The HTS research community should adopt a convention for tape length when reporting values of tape J_c.

f)

DC HTS cable designs have been conceived entailing consumption of more silver than is mined in the entire world in a given year.

If HTS cables were realized, the maximum size of the HTS cable market would be limited because at some size the world price of silver would be impacted. This problem would be aggravated if, as envisioned in some scenarios, HTS cables are utilized at lower-voltage/higher-current ratings than comparable copper conductors.

g)

A niche where HTS cable has a clear advantage over standard lines is in their ability to transmit many times more current within the same volume. Retrofitting HTS cables into existing conduits in urban areas to increase capacity is the most obvious application where this current-density advantage might confer a capital cost savings. The Japanese have the most concerted effort on this front. However, the first-such project has been announced in the US, at an estimated total cost of \$6261/kAm. On a \$/kAm basis, this is about 10 times more than the cost of HVDC underground capacity, and about 100 times more than for HVDC overhead line capacity.

Appendix 1: Tabulated Parameters for Prototype HTS Cables

Country	Denmark	Germany	USA	Japan	Japan	Japan	Japan
Company	Tech. U. of Denmark	Siemens	AMSC/Pirelli	Furukawa	Sumitomo Elect.	Sumitomo/TEPCo	Furukawa Electric
Year	1997	1997	1995	1995	1996	1995	1997
Reference	[55]	[38,77]	[53]	[52]	[40]	[78]	[79]
Cable:							
length (m)	1	10.5	1.04	5	50	7	50
I_c of cable DC- (A)	640	5000	4200	2050	2200	1500	1700
Theoretical I_c - # tapes x Ic,tape	c 1123	c 7900	c 6300		c 5144	e 6017	e 5487
Current Retention	**c 0.57**	**c 0.63**	**0.67**	**0.6**	**c 0.42**	**e 0.25**	**e 0.31**
total length of tape in cable, m		2000			3400		
# of tapes in cable	80	145	140		62	63	e 310
length per tape (m)		c 13.8			c 54.8	e 8	
# of layers	4	4	6		4	4	10
lay-angle (degrees from axial)		c 40.4	30		c 24	e 30	e 15
O.D. of former (mm)	25		33		19	19	32.5
O.D. cable (mm)					23	22	38
Tape							
J_c @ 77 K - kA/cm^2	12 to 14	c 25		7	27.8	e 32	10
Current per wire (A)	c 14	c 54	45	c 11	c 83	e 95.5	e 17.7
fill factor	0.2	0.25	0.3	0.25	0.26	e 0.26	e 0.3
width (mm)	3	3.5	3.56	2.5	4.1	e 4.1	3.2
thickness (mm)	0.18	0.25	0.28	0.25	0.28	e 0.28	0.185

c = directly calculated from provided information

e = based on most reasonable estimate possible given provided information

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