HIGH TEMPERATURE SUPERCONDUCTIVITY:

THE PRODUCTS AND THEIR BENEFITS

2002 Edition

Final Version

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PREFACE

The first version of this report was completed in July of 1998 and further revised in January of 1999. The second version was published in June 2000. This is the third version. This edition uses available Department of Energy (DOE), Energy Information Administration (EIA) data and projections through 2020. Projections at this time are developed based on an electric growth projection average of 2.5% per year, a projection developed by Bob Lawrence & Associates, Inc. (BL&A), based on historical information and assumptions that the future would present similar market pressures. This case is now accepted by EIA as its "high" scenario. The present document and its included analysis were developed using the database developed for the first and second edition of this publication, and modifying it appropriately based on programmatic and market changes between 1996 and the present. The latest comprehensive market data available is EIA information through December 2000. The latest programmatic data is from workshops and seminars during 2001 and 2002, supplemented by recent interviews with project principal investigators.

The dates of projected market entry for this report have changed from the original projections, largely due to the fact that the HTS product development programs have progressed to a point where market entry, or non-entry, has become a clearer task. Electric motors will be a later market entry than previously thought, and generators will be earlier. These changes are explained in the relevant sections of the report.

Since the cost differential of HTS technology and the value of non-energy savings benefits are not well defined at present, this benefits assessment does not attempt to quantify these values but considers instead only the quantity and value of the energy saved. One way to look at this is to consider that the discounted values of these non-energy savings benefits are equal to the cost differential between HTS and conventional technology. In this way, energy savings becomes the surrogate and driving force for the market penetration. If non-energy savings benefits are (as many suggest) greater than the first cost differential, market penetration may be expected to proceed faster than projected in this report. Of course all included market penetration models assume that production capacity can be established in the required time frame.

A complete list of facts and assumptions used for the analysis appears as Appendix I to this report, entitled "Foundations for Superconductivity Analysis."

Bob Lawrence & Associates wishes to thank the DOE Program Managers and the dedicated individuals of exceptional technical quality at ORNL who spent considerable time and effort providing key information and reviewing and editing this document. Their dedication contributed substantially to the quality and utility of this final report.

L. R. Lawrence, Jr.

EXECUTIVE SUMMARY

There is little question that superconducting technology will make a substantial impact on the way we generate, transmit, distribute, and use electric power. The question, of course, is, "When?" Although the potential benefits of low-temperature, superconducting materials have been known for some time, their widespread use has been precluded by the cost and energy required to achieve the very low temperatures of liquid helium and liquid hydrogen, since superconducting properties were originally known to exist only at these very low and hard to reach temperatures. All this changed when, in 1986, eight new materials were found which exhibited superconducting properties at the temperatures of liquid nitrogen (77 K), a temperature far easier to achieve, and far less costly in energy and dollars than that of liquid hydrogen and helium. Since 1986, substantial R&D programs in the U.S., Europe, and Asia have pursued the utilization of these high temperature superconducting (HTS) materials and their utilization in common electrical equipment.

Numerous qualitative studies have discussed, in detail, the projected benefits of the commercialization of HTS systems (see References); however, few studies with quantitative predictions of market penetration and resultant benefits are available. This report attempts to quantify those benefits, as a function of time, by examining five key classes of candidate HTS electrical equipment, and projecting market entry and capture based on historical market entry of technologies considered analogous to HTS. Any such projection is a judgment based on experience and available data, and the analyses in this report fall into that category.

Key to the analyses is the list of facts and assumptions found in Appendix I entitled "Foundations for Superconductivity Analysis." These were developed based on an exhaustive review of the presented References and discussions with utility and technology experts. The facts and assumptions, then, drove the resulting analyses, which arrived at the conclusions found in this report.

The exact capital cost differential between conventional and HTS technology and the values of non-energy benefits are not presently well defined. A major assumption of this analysis is that these values will be offsetting and hence, the value of net energy savings is taken as the driving force for market penetration. Alternatively, the capital cost differential can be taken to be zero and these operational benefits ignored. Future valuation of these operational or non-energy benefits may well be greater than the capital cost differential which would tend to accelerate market penetration provided the production capacity can be installed to meet this demand in the required time frame. The five classes of equipment examined are electric motors, transformers, generators, underground cable, and fault current limiters. In each of these classes, major, international programs are now underway to develop and commercialize HTS equipment in a time frame from the present to the year 2020. Based on technology status and perceived market advantages as determined from the references, market entry dates were projected, followed by market penetration predictions. The earliest equipment to achieve commercialization is now predicted to be superconducting cable, predicted for market entry in the early 2005 time period. U.S. transformers are also projected for entry later in 2005, followed by electric motors in 2008. The final market entry will be generators, predicted for commercialization in 2009.

A key point in the analysis is the point at which the equipment will capture 50% of the potential market. The results predicted are as follows:

Table ES-1: Year of 50% market penetration.

Equipment:	Motors	Transformers	Generators	Underground cable
This year sales: 50% of Market	2018	2015	2019	2013

The case examined to predict benefits for market penetration of this equipment is based on electrical generation and equipment market growth averaging 2.5% per year through 2020. This percentage was chosen based on historic figures from 1990 - 2000 and the assumption that a similar economy will continue on a comparable scale. Benefits calculated are determined by the value of electricity saved that would otherwise be wasted. As indicated above, operational benefits are not quantified in this report, although many are suggested.

Annual benefits from all equipment types considered will be $212 million in 2010, $2.37 billion in 2015, and $12.6 billion in 2020. Cumulative benefits are $377 million in 2010, $6.33 billion in 2015, and $44.5 billion in 2020. The projected benefits of this technology are clearly substantial. All values are in constant 2000 dollars.

Environmental benefits from the installation of HTS technology accrue in two forms. First, the higher efficiency of electric generation, transmission, distribution, and utilization results in a lower generated power requirement, resulting in lower greenhouse emissions to the atmosphere. Second, the highly efficient characteristics of HTS transmission and distribution (T&D), along with its high energy density, make electricity generation from renewable resources and in remote locations economically viable. Construction and legal costs, overhead transmission (versus underground transmission), and right-of-way issues are all precluded by these inherent features, benefiting, along with the larger populace, distant population centers with limited access and resources.

In summary, the calculated benefits to American society through commercialization of this technology are predicted to be immense. These benefits do not include the major, worldwide markets, which American industry will serve, assuming the U.S. has the technological lead in this area. Whether examining the economic and environmental benefits of the technology or the jobs and markets to be gained, the evolution of HTS equipment is clearly a viable and critically important goal to pursue.

INTRODUCTION AND BACKGROUND

The 20th Century was replete with revolutionary technological advances, and when these advances made their way into the marketplace, significant and substantial changes in our nation's productivity and standard of living resulted. Prominent examples of such are solid state electronics, plastics technologies (including polyester), and aircraft materials that allow for high speed flight. More recently, computer memory technology has impacted our lives, with hard drives going from tens of megabytes in the 1980s, to tens of gigabytes today. In virtually every case, the "breakthrough" technology has been catalyzed by a fundamentally new understanding of the properties of a material or class of materials prepared in new and different ways. The purpose of this report is to examine, inasmuch as possible, the market emergence of another whole new class of materials with unique properties; to be explicit, high temperature superconducting (HTS) materials and their applications.

By definition, superconductivity is the property of a material to conduct unusually large quantities of electrical current with virtually no resistance. Since 1911, researchers have known that certain materials show superconducting properties when they approach a temperature near absolute zero. However, other than magnetic resonance imaging and kaolin clay separators, few industrial or commercial applications have developed for these materials, since they are characteristically costly to make and prohibitively expensive to cool to the required temperature of liquid helium (4 K). The energy required to cool to 4 K is about 25 times that required to cool to 77 K, the temperature of liquid nitrogen. Considering also the added cost of the helium gas, liquid helium costs about $5.00 per liter (1) whereas liquid nitrogen is only $.10 per liter. Thus, the cost and energy advantages of materials that are superconducting at 77 K are readily apparent.

A dramatic change occurred in the potential application of superconducting materials when, in 1986, a new class of ceramic materials showing superconducting properties at temperatures up to 34 K was discovered. Within six months of the publication of this discovery, eight new materials were found with superconducting properties at temperatures closer to that of liquid nitrogen (77 K), a temperature much more readily achieved and significantly less costly to produce. The materials themselves, however, remain costly to manufacture and very brittle in nature. Regardless, they have generated great excitement, since the projected costs of applications have dropped by orders of magnitude, long-length wires have been produced, and first viable products appear to be within reach.

Market acceptance of revolutionary products is itself a challenge, but once operational reliability and product advantages are known and accepted, and pricing is in an acceptable range, the products can rapidly take off and dominate their market in a decade or so. Analogous to this is the replacement of vacuum-tube electronics by solid state electronics. Driven by weight, ruggedness, and cost needs of the Space Program, solid state electronics were first introduced as individual components, then as small, discrete systems (radio signal receivers), and finally, as complete systems (solid state TV sets, computers), nearly replacing vacuum tube technology altogether. Because of the initial higher price of solid state electronics, their first applications were in space and military systems where their weight and ruggedness advantages justified the higher price. But increased use led to greater production, thereby leading to wider availability and lower price, leading to further increased use, creating a self-perpetuating market. It is reasonable to assume that, in the context of this report, superconducting products will follow an analogous path.

Another technological analogy that is interesting to examine when projecting the market entry of superconducting products is that of high efficiency gas furnaces. Superconducting products will attempt to penetrate utility markets, which are characterized by cost-conscious, reliability minded, fiscally conservative decision makers, not unlike the natural gas appliance market. Utility markets are a well-established market-- predictable, and lacking in significant dynamics. In 1977, the high efficiency furnace was a revolutionary technology, with the demonstration of "pulse combustion" technology. At that time, the standard gas furnace for home heating was 55% efficient, non-condensing, with a high exhaust temperature meant to minimize corrosion in the heat exchanger during the projected 30-year lifetime of the product. The pulse combustion furnace was a radical technology departure in that market, operating at efficiencies of up to 98%, and including high technology components and "condensing" exhaust gases. The high efficiency furnace went from a single laboratory item to a twelve-unit test in the 1979-1980 time period. The test was conducted first in the laboratory, then in the field, with results showing acceptable reliability, customer acceptance, and a justifiable price differential, based on the 50% gas savings. Today, virtually all gas furnaces sold are above 90% efficiency, including both the pulse combustion and other new, high efficiency technologies. It shows that when multi-unit field tests (or demonstrations) of a new technology prove out the operational and financial advantages of the technology, it can rapidly penetrate and dominate the market, even when the market has a long history of being highly conservative. Superconducting products have the potential to follow a similar path.

Today, a number of HTS-based pieces of electrical equipment are at the prototype stage with capable manufacturing entities intimately involved. Early candidates for commercial products include transformers, electric motors, generators, fault current limiters, and underground power cables. Later in the commercialization process, replacements for overhead transmission lines are also foreseen; however, this will not be an early application. To enhance and accelerate the prospects for early commercialization of HTS products, the Department of Energy (DOE) has developed a vertically integrated program in which product-oriented teams are focused on the development and implementation of pre-commercial HTS equipment. Under the title of the Superconductivity Partnership Initiative (SPI), these vertically integrated teams typically each consist of an electric utility, a system manufacturer, an HTS wire supplier, and one or more national laboratories. Supporting these vertical teams is a Second Generation Wire Initiative, in which development teams are "exploiting research breakthroughs at Los Alamos and Oak Ridge National Labs that promise unprecedented current-carrying capabilities in high-temperature superconducting wires (2)." Since superconducting wire is the main component of all superconducting cables, products, and systems, the price drop and performance increases projected by the Second Generation technology is highly significant and exceptionally important to successful commercialization.

THE MARKET

If there are any words to describe the electric demand and generation markets over the next 20 years, two of the words must be "unpredictable" and "dynamic." When the prior "Products and Benefits" report was published in June of 2000, the future markets were described as "dynamic," but the California experience of 2001 could not have been predicted by anyone. The last full version of this Products and Benefits report was published based on available information and references at that time. Markets, then, were predictable and stable by comparison, with Bob Lawrence & Associates (BL&A) predicting demand and generation growth with considerable accuracy, based on historical facts and data and relating them to future assumptions. This, coupled with R&D program plans and continuing success in HTS product developments, led to a credible analysis predicting future markets.

In the past two years, both the electric industry markets and the product development R&D programs have seen dramatic changes, more in 2001 than 2000. In the electricity marketplace, we have seen dramatic shocks as a result of restructuring combined with more demand than supply, due to both natural and structural causes. The September 11 tragedy, due to the terrorist attacks, has brought a new focus on "Grid Security", and a concurrent change in market focus. ENRON, purportedly the shining example of how deregulation was to create an American energy market future, is now bankrupt, its executive corps facing possible jail time. The ENRON deregulated approach is in such disfavor, along with the California debacle, that any form of Federal deregulation of electric markets is unlikely in the near future.

Calpine, Williams, and Dynegy corporations, strong leaders in merchant power plant development for future electric generation have been strongly and negatively affected by the ENRON debacle. Once the darlings of the stock market, these companies have seen their shares fall to 20% or less of their former values. Calpine, for example, with an exemplary track record and strong performance, has its stock selling at 1/3 the corporate book value, and at a price/earns ratio in the range of 4, an unheard of low value for a company with its strong track record. This "domino effect" has, in turn, harmed the capability of merchant power generation builders to obtain the credit necessary to build power plants our country will need in the future.

The electric transmission situation in this country is nothing short of a disaster--ever present, continuously developing, and apparent for the foreseeable future. Path 15, in California, is just a small example of what the rest of the country will soon face. It is hoped that a significant National Transmission Grid Study, headed by Senior Policy Advisor Jimmy Glotfelty at the Department of Energy (DOE), can provide a database and structure for appropriate policy changes and investments, which will lead to a brighter future.

On a calendar year basis, the Energy Information Administration (EIA), at the DOE, publishes extensive historical data in its Electric Power Annual, Volumes I and II (3, 4). Available generally in "advance" form in August of the following year, and in final form in December, the information contains both annual data for the subject year as well as historical data for previous years. In addition, EIA publishes its Annual Energy Outlook in the December/January time period of each year, making broad energy projections. For the past five years, BL&A has projected electric demand growth of 2.5% per year, while EIA has steadfastly projected 1.4% growth BL&A has been consistently, substantially correct, while EIA has been dramatically off. After consistently underestimating by about 44% for several years, EIA raised its projection last year to 1.8% average annual growth from the present until 2020. The newly published Electric Power Annual 2000 shows that, once again, electric growth in 2000 was 2.6%, in contrast to the recently amended EIA projection. This is a miss of 31%. In the defense of EIA, they now acknowledge, in their Annual Energy Outlook 2000, that there is a credible case for a projection of 2.5% growth.

When the economy was strong, and there were no national crises, the United States could afford inaccurate projections like this without significant consequences. However, with the crises that we now face, economically, strategically, financially, in the policy arena, and in national security, it is essential that EIA find the reason for its continuing failure at reasonably accurate projections and make appropriate corrections forthwith. Of deeper concern is that the electric projections appear to come from the rather massive, all encompassing computer models touted by EIA. With this continuing, erroneous outcome, it calls the validity of the entire model into question. It is absolutely essential that the country have better energy prediction capability for proper policy guidance and a more reliable future. That said, when the data comes in from 2001, it is likely to be a dramatically different year. It may even be a year in which electric demand declines rather than increases. In deference to the EIA, large target that it is, it was impossible to predict all the negative events that happened in that one single year (California electric crisis, September 11, economic recession, war, homeland defense, ENRON) and their effects on electricity demand and generation. It is also very hard to predict the long-term effects to the economy of this unique year. All that can be said is that the effects can only be economically negative, with a yet-to- be-seen affect on the projected electric demand for the near future.

Table Mkt-1: Electric Generation and Use
Utilities and Non-utilities
1989 through 2000

Year	Net Generation Billion kWhrs	Percent Increase	Total End Use (Billion kWhr)	Percent Increase	Losses & Unaccounted	Losses (%)
1989	2972		2747		236	7.94
1990	3025	1.78	2817	2.55	210	6.94
1991	3071	1.52	2873	1.99	218	7.10
1992	3083	0.39	2885	0.42	224	7.27
1993	3197	3.70	2988	3.57	236	7.38
1994	3254	1.78	3075	2.91	223	6.85
1995	3358	3.20	3162	2.83	235	7.00
1996	3447	2.65	3250	2.78	237	6.88
1997	3494	1.36	3295	1.38	234	6.70
1998	3618	3.55	3424	3.92	220	6.08
1999	3706	2.43	3501	2.25	234	6.31
2000	3792	2.32	3607	3.03	221	5.83
Average Increase		**2.24%**		**2.51%**		**6.23%avg (Last 4 Years)**

In projecting future electric growth, BL&A subscribes to the following rationale:

a) There is no immediate or readily apparent reason to believe that economic growth over the next 20 years will be a different average than the past 15 years (since 1986), once our economy is past the effects of 2001;

b) The effects of user efficiency increases vs. needed generation increases over the past 15 years have set a pattern which shouldn't differ greatly between now and 2020;

c) The economic growth prior to 2001 was largely based on electricity-using computers and manufactured items, which incorporate electricity-using computers;

d) The pace of technology improvements in computer-based and computer-related technologies is such that a pattern of expansion of computer-integrated technologies, electricity using, is seen in more and more aspects of human life;

e) Electric demand will drive electric supply. Therefore, the demand average growth of 2.5% must also be taken as the projected generation growth.

For these reasons, BL&A believes that it is realistic and intellectually correct to continue with the projection of an average 2.5% annual generation growth for the next 20 years.

Table (Mkt-2) shows a projection of Electrical Industry Capability, Net Generation, and Total End Use from 2000 (hard data) through 2020, projecting 2.5% average growth from 2000 forward.

Table(Mkt-2) Generation and End Use Projections
At 2.5% Average Growth per Year

Year	Generation Billion kWhr	End Use Billion kWhr	Avg Cost Cents/kWhr (EIA Projection)	Required Capability (MkW)
2000 (Actual)	3792	3607	6.3	818.5
2001	3887	3697	6.9	839.0
2002	3984	3790	6.8	859.9
2003	4084	3884	6.7	881.4
2004	4186	3981	6.6	903.5
2005	4290	4081	6.5	926.1
2006	4398	4183	6.4	949.2
2007	4507	4288	6.3	972.9
2008	4620	4395	6.3	997.3
2009	4736	4505	6.3	1022.2
2010	4854	4617	6.3	1047.7
2011	4975	4733	6.3	1073.9
2012	5100	4851	6.3	1100.8
2013	5227	4972	6.3	1128.3
2014	5358	5097	6.3	1156.5
2015	5492	5224	6.3	1185.4
2016	5629	5355	6.4	1215.1
2017	5770	5488	6.4	1245.4
2018	5914	5626	6.5	1276.6
2019	6062	5766	6.5	1308.5
2020	6214	5910	6.6	1341.2

Utilities are largely aging systems with aging equipment. For example, 70% of transmission lines are over 25 years old; 30% of transmission lines are over 50 years old; 70% of transformers are more than 25 years old and 60% of circuit breakers are more than 30 years old (5).

In this environment of deteriorating statistics, electricity providers are seeing a market with a demand for ever-increasing reliability requirements. Today's electric system provides approximately 99.9% reliability. A large and growing number of electric consumers desire 99.9999% or higher reliability--essentially perfect power (5). Urban and environmental requirements are driving towards a strong, robust grid, with the smallest possible environmental and land use footprint (5), an opportunity for superconducting options that fit within those parameters. The question is how to get there from here, and the characteristics of superconducting product designs are such that they appear to present some meaningful solutions.

As seen in Table (Mkt-2), 523 GW of new generating capacity will be needed by 2020 to meet growing demand and replace retiring units, assuming that the BL&A projections continue to remain correct. Assuming an average 800 MW per plant, this means 654 new plants will be needed by 2020. Not surprisingly, over the next 20 years, an electric generation shortfall is projected (5).

In the AEO 2000 forecast, it is no longer assumed that the average price of electricity will simply drop. Due to the new average demand projection of 1.8%, EIA assumes that the average price will decline slightly, to 6.3 cents per kWhr in the mid 20-teens, increase as 2020 approaches. In their high case of 2.5% growth (the BL&A case), EIA expects to see electric prices follow the pattern shown in Table (X).

In the electric power market, generation (and initial transmission) is shifting dramatically from utility ownership to independent power producers. The Electric Power Annual 1998: Volume I (6) reports, "As of January 1, 1998, [a] net summer capability of 778,513 Megawatts existed to supply electricity in the United States. At that time, the electric utility sector owned...a capability of 711,889 MW, accounting for approximately 91% of the total. During the year, however, the share of the total industry capability owned by non-utilities rose from 9 to 12%, primarily as a consequence of the sale of generating units by utilities to non-utility companies." During 1998, 593 MW of capability was added. Non-utilities presently plan 62 GW in capacity additions for 1999 thru 2003. Utilities plan 28 GW in additions (3), a factor of two less.

In this future market scenario, and with an increasingly, environmentally conscious public, it is clear that more efficient technologies, occupying smaller footprints will have a desired place in the electric industry. Clearly, the cost of HTS equipment will be crucial to the development of this market.

ULTIMATE BENEFITS

Factoring in the full implementation of the superconducting technology candidate systems and products, dramatic cost and energy savings are projected, with incremental benefits accruing from the time of technology readiness and commercial introduction to the time of full market penetration. As mentioned earlier, the primary candidates for commercial products include transformers, electric motors, generators, fault current limiters, and underground power cables.

At present, all of these items are based on aluminum and copper materials (except for current limiters, which are a new device). Starting with aluminum wire and steel structural cable, transmission cables are formed. Aluminum forms the basis of squirrel cage induction motors. From copper wire, armatures are wound for electric motors, and coils are built for generators, transformers, and relays. Aluminum and copper distribution cables have been placed under streets, and copper electric wiring has been placed in buildings, houses, commercial establishments, industry, and all other structures that exist in modern countries.

Much of this will change when superconducting materials become the standard for electrical equipment. When fully implemented into the electric generation and utilization sectors of our economy, this technology is expected to save $8 billion per year in retail value of electricity presently lost in the T&D process through aluminum and copper-based infrastructure. An additional $8 billion per year can be saved with the installation of superconducting transformers and electric motors (7). Yet another $2.24 billion can be saved through full implementation of HTS generators. Hence a total of $18.24 billion savings per year, resulting from full implementation of HTS technology, in presently envisioned equipment. Oak Ridge National Laboratory (ORNL) experts and studies carried out by Energetics, Inc. indicate that HTS underground cable savings would be in the range of 125,000 kWhr per mile, per year.

The complete application of superconducting technology in generators, power transformers, underground transmission lines, and in large commercial/industrial sector motors can reduce the amount of electricity (and primary fuel) needed to provide the same service by 4 to 5%. The two key technical items holding back this perceived market is the remaining need to "turn [superconducting] ceramics into robust, cost effective, components that can survive industrial manufacturing and assembly (1)," and the need for high reliability, cost acceptable, cryogenic refrigeration.

Richard D. Blaugher of the National Renewable Energy Laboratory has described the market introduction of HTS equipment into the electric utility marketplace and industrial environment by succinctly stating that the general acceptance of superconducting power equipment by the electric utilities and other end-users will ultimately be based on the respective system performance, efficiency, reliability and maintenance, operational lifetime, and installed cost compared to conventional technologies (8). Surveys conducted as a part of this present study indicate similar findings. In general, these parameters and their values must be proven first in single prototypes of candidate commercial equipment, followed by multiple-unit field testing with acceptable results. Only then will significant market penetration begin.

METHODOLOGY FOR MARKET PENETRATION

The methodology to predict market penetration and resultant benefits, as a function of time, requires a number of assumptions, based on the present state-of-the-art of the technology and the present and projected status of the target markets. Some of these key assumptions are:

a) Date of technology maturity (readiness for one or more markets).

b) Date of market entry and percent of market captured as a function of time (the classic "S" curve).

c) Amount of new installations and amount of replacements as total market and as a function of time.

d) HTS percentage of total product produced by original manufacturers of cable, electric motors, generators, transformers, and current limiters.

e) Other secondary assumptions such as economic projections, population growth, etc.

Clearly, based on the needed set of assumptions, predictions of market growth and market penetration by superconducting products can have a wide range of results. In order to credibly carry out this analysis in the most credible fashion, the authors have endeavored to access the most reliable available information regarding the above parameters.

For each potential product addressed, a date of technology readiness is assumed to be the date at which multiple-unit field tests are initiated, based on the results of successful prototype or "pre-commercial" single units. Following the field test, assumptions are made regarding manufacturing readiness and percent of market penetrated. Based on interviews and references surveyed during the past years, a prediction is made as to the timing of 10% market share of each product, 50% market share, and ultimate market share. These things then determine the shape and timing of the market penetration "S" curve.

The broad, general assumptions and facts governing the market penetration projections may be found as Appendix I at the end of this report, entitled, “Foundations of Superconductivity Analysis.”

ANALYSIS

The analysis portion of this report is broken down by target product and market. In other words, individual sections cover the five candidate products: transformers, electric motors, generators, fault current limiters, and underground power cables. In each case, there are two key milestones to be considered: The operating demonstration of a "pre-commercial" product, which defines initial costs and design considerations for the target product; and the multi-unit field test. Undoubtedly, the most important defining point of market entry is the multi-unit field test, because this test requires tooling for multi-unit manufacturing, and also requires serious investments on the part of the potential manufacturer/distributor of the candidate product. The decision to make these serious investments must, of necessity, come from detailed cost and market studies which lead the manufacturer to believe that the market and the product specifications match to the point of a profitable and growing business projection. All values in this report are expressed in constant 2000 dollars.

Another aspect of the multi-unit field test is that it requires training in operation and maintenance. Whereas a single unit demonstration can be carried out in a laboratory with engineers and scientists who are very familiar with the technology and the equipment, a multi-unit field test will require the involvement of a number of people who are experiencing the potential product for the first time. Therefore, education and training, manuals, parts availability, and all the beginnings of a logistics chain must be put into place.

Thus, for the purpose of this study, and based on past experience, the authors are assuming that 10% market penetration will occur within five years of the successful testing of multiple units in the field, in the hands of potential buyers. This will increase to 50% of the market after an additional five years. This second assumption is based on present data showing the present attractiveness of high efficiency equipment in the electrical equipment markets. Final market share is analyzed separately for each potential product. While some analysts may question these assumed S-curve parameters, it is not difficult to alter the market penetration model to either accelerate or slow the technology entry rate and to recalculate the resultant benefits based on individual, technical judgment.

ELECTRIC MOTORS

THE MARKET

Electric motors consume over 60% of the total industrial demand for power (9).

A promising scenario exists for the market penetration of electric motors based on HTS technology. Extensive information on electric motor use and markets can be found in the Xenergy publication: "U.S. Industrial Electric Motor System Market Assessment (10)." This appears to be the latest study available with information as comprehensive as it has. This document restates the conclusion of an A.D. Little study that average annual hours of use for motors below 5hp is in the range of 250 hours, while average use for motors over 50hp is in the range of 3500 hours per year. From the Xenergy study, statistical samples indicate that average use for larger motors ranges from 3200 to 5200 hours per year. For the purpose of the present study, an average use for large motors is assumed to be 4200 hours per year.

The SPI team developing electric motors is led by Rockwell Automation/Reliance Electric (systems manufacturer) and comprises American Superconductor (wire manufacturer), Centerior Energy (utility end user), Air Products and Chemicals (industrial end user and cryogenics supplier), FirstEnergy, and Sandia National Laboratories. The motors being developed are in the "large motor" category (greater than 1000hp) whose primary applications are drives for pumps, fans, and compressors in utility and industry markets. The primary markets to be addressed will be continuous operation markets. Large motors convert 30% of all U.S. electrical energy generated, 70% of which are well suited to utilize HTS technology. The worldwide market for HTS motors greater than 1000hp is estimated to be $300 million per year (11).

The Bureau of the Census, working with the Energy Information Administration, produces further information within the "Current Industrial Report - Motors and Generators (12)." This report indicates that the total motors and generators market for 1997 was $10.25 billion, declining slightly, but essentially level since 1995. The level of detailed information available in this 1997 report does not seem to have been repeated since. Energy efficient motors, however, continue to increase as a percentage of sales (12), showing the increasing market desire for energy efficiency. Electric motors continue to increase as a percentage of electric energy use, moving from 53% of all electricity consumed in 1993 (10) to 64% in 1996 (8). It is indicated that the percentage remained at 64% through 1998 (5). The authors found no later data to contradict this. As a percentage of total motor kWhr, electric motors are distributed among residential (23%), commercial (20%), utility (13%), and industrial applications (44%). An EPRI study further estimates that the distribution of installed capacity of electric motors in industry is 50% above 50 hp and 50% below 50hp (10, p. 3-11). "Above 126 horsepower" represents 33.3% of the total market, indicating why the Reliance team for its first demonstration motor chose this design point.

“The HTS motor cuts losses in half compared to an energy efficient AC induction motor. Furthermore, the HTS motor has an active volume that is 55% of an 1800 rpm, 5000hp, high efficiency induction motor. This leads to reductions in friction and windage, core, stray load, and armature I^2R loss (11).”

The Worldwide market for HTS motors greater than 1000hp is estimated at $300 million per year. The SPI team is presently working on a design effort for a 5000hp motor. Advanced component demonstrations for this motor are now underway. The AC induction motor represents the most challenging competitive market. A major advantage is that the 5000hp HTS motor has an active volume of only 55% of that of a conventional, 1800 rpm, 5000hp, high efficiency induction motor (13).

In a press release dated February 20, 2002, American Superconductor announced the receipt of a new contract to build a 6500hp motor designed for ship propulsion. In this same release, CEO Greg Yurek describes plans to have these motors commercially available for sale in 2004.

"Motors of this type will revolutionize markets, such as marine propulsion and power generation, through the introduction of highly compact and efficient HTS machines and systems," said Yurek. "We believe we're on track with our earlier forecast of having commercial HTS ship propulsion motors available for sale in the 2004 time frame (14).”

Industry analysts forecast the conversion to electric ship propulsion will accelerate the growth of the current $400 million ship propulsion motors and generators market to $2-4 billion annually in the next 10 years. The expected compound annual growth rate for electric motors and generators for ship propulsion applications is expected to be more than 20%. Today nearly 100% of all cruise ships and many cargo ships have transitioned to electric motor propulsion systems. In 2000, the U.S. Navy also announced its intention to transition to electric propulsion motors for future Navy ships.

The attractiveness of efficient motors over standard motors has been increasing as illustrated in the following Table M-1 taken from Reference 15. The data in this table can be used to estimate the percent of efficient motor sales. From 1993 to 1995, efficient motors increased market share from 19.2% to 20.3%. As mentioned above, this trend continues today (12). Thus, efficient motors are increasing as a percentage of total sales while “standard” motors are decreasing. This bodes well for the introduction of HTS technology into the marketplace.

Table M-1: Trends in average unit value of manufacturer's shipments efficient and standard motors.

Motor Type:	1993	1994	1995
Standard	$457	$448	$410
Efficient	$592	$599	$627
All	$483	$478	$454

From the preceding information and the Appendix I facts and assumptions, the defining market to be addressed by HTS equipment is motors above 50 hp. By examining the wealth of data in Reference 10, this market uses approximately 70% of all electricity used by electric motors. From the list of facts and assumptions, 64% of all electrical power passes through electric motors and, in 2000, total sales of electricity to ultimate customers was 3607 billion kWhr growing at 2.5% per year. Therefore, the market to be addressed by HTS motors over 50 hp is a market using (.7 × .64 × 3607) = 1616 billion kWhr (2000) growing at 2.5% per year. Approximately 6% of the market inventory fails and is replaced every year, and another 6% is rewound. The second paragraph in this section suggests that possibly only 30% of electric motors are viable candidates for HTS technology resulting in a 57% reduction in savings to (.3 × .64 × 3607) = 693 billion kWhr (2000) growing at 2.5% per year. The two values bound the range of savings that would result from HTS motor applications. The reader may reduce the benefits and savings in Table M-2 to reflect this change if so desired.

TECHNOLOGY STATUS

As mentioned earlier in the report, Reliance Electric with American Superconductor Corporation as the HTS coil supplier and manufacturer leads the U.S. HTS electric motor team. Also on this team are FirstEnergy (a utility company), Air Products and Chemicals, and Sandia National Laboratories. This team has designed, built, and successfully tested a four-pole, 1800 rpm, 200hp, synchronous motor using HTS windings operating at 27K at a continuous 150 kW output. This output was some 25% above the motor design (15). It is safe to say that the promise of the HTS technology has been shown by this demonstration. An additional demonstration of a 1000hp motor began in July 2000, and once again, the performance exceeded the design parameters. This program has now been extended to "develop a pre-commercial prototype of a 3.7-MW (5000hp) HTS motor" (15). The demonstration of this motor will be an important milestone in the commercialization process, since it will provide a measure of efficiency, reliability, and projected costs and benefits. With these two demonstrations accomplished, the market will have been bracketed with these two size ranges, and the next step will be the multi-unit field test previously described.

The final goal of this partnership program is to design and operate successfully, in an appropriate environment, a 5000hp superconducting motor. Rotor prototypes for the 5000hp motor are presently under test (16).

The worldwide market for HTS motors greater than 1000hp is estimated at $300 million per year. The SPI team is presently working on a design effort for a 5000hp motor. Advanced component demonstrations for this motor are now underway. The AC induction motor represents the most challenging competitive market. A major advantage is that the 5000hp HTS motor has an active volume of only 55% of that of a conventional 1800 rpm, 5000hp, high efficiency induction motor (13). This would provide added incentive to consider HTS technology even without net life cycle cost benefits from energy savings.

As with virtually all HTS products, the cost drivers for HTS motors are the refrigeration and wire costs. At this point in time, the 5000hp motor is seen as a “verification tool” whose final commercialization is dependent on wire costs. There is a question as to whether BSCCO technology can get there in price, even making the present goal of $10/kA-m. It is anticipated that $2-4 per kA-m is really needed for broad market penetration (16). It is hoped that the coated conductor wire technology can come closer to meeting these cost goals. The motor refrigeration system presents a unique set of problems in that the design maintenance cycle time is one year (17).

Overseas, the Siemens motor, operating at 550hp, uses BSCCO superconducting tape manufactured by Nordic Superconductor Technologies (NST) of Birkerrod, Denmark (18). Operation of the motor will be at 25-35K, clearly not a commercial design for industrial applications. Siemens indicates that initial markets for this design are electric ships and oil platforms, where energy density is worth a premium.

American Superconductor of Westborough, Mass. has announced results of its 5000hp superconducting motor prototype. According to a company press release of January 16, 2002, American Superconductor has "successfully completed load testing of the world's first 5000hp, high temperature superconductor (HTS) prototype electric motor." The press release added that the company is also continuing with its plan for the design, manufacture and testing of its first ship propulsion motor prototype, a much higher torque, lower speed motor than the prototype 5000hp motor.

Much more development work lies ahead. One challenge: HTS wires lose their vaunted high-temp powers in the presence of magnetic fields, although superconductive properties can be restored with further cooling. Since all motors and generators produce magnetic fields, HTS models using BSCCO wire will have to be cooled with expensive helium--until newer, second-generation HTS materials can be produced in volume (19).

MARKET PENETRATION

The 5000hp motor development for commercial applications, led by Rockwell Automation, has slowed down with program revisions. Because of the continuing high costs of near term HTS wire, Rockwell envisions the commercial market to be a longer term target than originally thought. The program is now structured to advance critical supporting technologies while waiting for HTS wire cost advancements (20). Therefore, commercialization and the market for these motors may be further off than originally predicted. BL&A estimates a market delay of two years compared to the earlier predictions made in the 2000 “Products and Benefits” report.

Demonstrations in an appropriate user environment are necessary for market development and commercialization to take place. The 1000hp and 5000hp motors are being developed for this purpose (16).

For the purposes of this study, then the multi-unit test is projected to begin in 2007, with 10% market penetration achieved by 2013. By 2018, 50% market penetration would be expected to occur, with the market share leveling from that point in the typical “S” curve. Benefits for each year are calculated as follows:

a) Market growth is 2.5% per year.

b) Percent of electric motor use addressed by HTS market: 70%.

c) Percent of electric motors over 50 hp replaced or added annually is 6% replaced and 2½% added for a total of 8½% market change per year.

d) Electric motors use 64% of all electricity delivered for end use.

e) Installed HTS technology motors will save 2.2% of total electricity used by electric motors (98.1% HTS efficiency vs. 95.9% present practice).

f) The price of electricity changes as shown in Table (Mkt-2).

g) The discounted capital cost differential between the HTS and conventional technology just offsets the non-energy savings benefits and is not considered in projected energy and cost savings.

Therefore, benefits (kWhr saved in year N) are calculated as: $(3{,}607 \times 10^9$ kWhr$) \times$ (Market Growth factor = 2.5%/yr for N years) × (.64) × (.7) × (% penetration in year N) × (2.2% saved).

For the first 30 years of market penetration, it is assumed that no HTS motors are replaced (30-year lifetime). Therefore, all annual benefits, due to market penetration, are cumulative. The following table projects this process:

Table M-2: Market Projections and Benefits for Electric Motors
Generation and End Use Growth Assumed to be 2.5% per year.
Year 2000 numbers are actual.

Year	End Use B-kWhr	Avg Retail Cost Cents/kWhr (EIA Projection)	Market Penetration (%)	This Year Sales Energy Saved (B-kWhr)	Annual Energy Saved (B-kWhr)	This Year's Sales Benefits ($M)	Annual Benefits ($M)
2000	3607	6.3	0	0.00	0.00	0	0
2001	3697	6.9	0	0.00	0.00	0	0
2002	3790	6.8	0	0.00	0.00	0	0
2003	3884	6.7	0	0.00	0.00	0	0
2004	3981	6.6	0	0.00	0.00	0	0
2005	4081	6.5	0	0.00	0.00	0	0
2006	4183	6.4	0	0.00	0.00	0	0
2007	4288	6.3	0	0.00	0.00	0	0
2008	4395	6.3	1	0.43	0.43	27	27
2009	4505	6.3	2	0.89	1.32	56	83
2010	4617	6.3	3	1.37	2.69	86	169
2011	4733	6.3	5	2.33	5.02	147	316
2012	4851	6.3	7	3.35	8.37	211	527
2013	4972	6.3	10	4.90	13.27	309	836
2014	5097	6.3	15	7.54	20.80	475	1310
2015	5224	6.3	22	11.33	32.13	714	2024
2016	5355	6.4	31	16.36	48.49	1047	3103
2017	5488	6.4	40	21.64	70.13	1385	4488
2018	5626	6.5	50	27.72	97.85	1802	6360
2019	5766	6.5	60	34.10	131.95	2216	8577
2020	5910	6.6	68	39.61	171.56	2614	11323

This table shows that by 2010, HTS motors will save a cumulative 4.44 billion kWhr equivalent to $0.280 billion. By 2015, this becomes 84.03 billion kWhr or $5.29 billion. And finally, by the end of 2020, this technology will have saved a cumulative 604.01 billion kWhr or $39.86 billion. If only the largest motors (> 126 hp) are considered, the reader may reduce the table values by 57% as indicated above.

TRANSFORMERS

THE MARKET

HTS Transformers offer the following economic, operational, and environmental advantages: Higher efficiency; 2X rating overload capability without insulation damage; lower impedance and better voltage regulation; potential for fault current limiting capability; reduced cost for associated switchgear, breakers, etc; lower environmental hazard due to lack of oil; and lighter and more compact than conventional units (22).

The existing U.S. transformer market for 10-100 MVA power transformers is $550M and $302M for transformers larger than 100MVA. The world market is 3-4 times larger and growing twice as fast (23).

There are over 40 million distribution transformers in use in the United States. The Environmental Protection Agency (EPA), in its report, "Transforming Dollars Into Sense: The Economic and Environmental Benefits of High Efficiency Transformers," states that 61 billion kilowatt hours annually are lost due to distribution transformers. The report estimates that 0.1% improvement in efficiency in 1 million transformers sold in one year would save 2.9 billion kilowatt-hours of electricity (23). Because of increased loading levels and inherent higher efficiency, a 0.1% increase in power transformer efficiency would provide even greater benefit.

From the facts and assumptions in Appendix I, all generated electricity goes through nominally three stages of transformers: one up and two down, between the generator and the meter at the final point of use in the distribution system. Approximately 50% of all electricity faces at least one more stage of transformation between the meter and the end-using device. Therefore, for each 1 MVA of generating capacity there are 3 to 4 MVA of transformer in place (24). For the purpose of this analysis, it is assumed that all generated electricity is transformed three times between the generator and the final distribution transformer.

One-half of all U.S. power transformer sales will be in the class of 30 MVA, 138-kV/13.8-kV transformer rating for the next two decades (25). This is a prime target portion of the market for market entry. Power transformers are about 99% efficient. Even though they are rated at 99.3 to 99.7% for the 30 MVA, 138-kV/13.8-kV class, they are purchased with excess capacity to meet maximum temperature limits. Therefore, they operate well below design load for the majority of the operating period and typical evaluation programs force the design to produce the maximum efficiency at or near the expected average loading (design load) point. Indeed the full load efficiency is below maximum efficiency. Nevertheless, power transformers are responsible for 25% of all transmission/distribution losses (25), or $2 billion annually. A 30/60 MVA HTS

Transformer requires about 5000 kA-Meters of conductor for less than $75,000 to be commercially viable. Therefore, the target price/cost of conductors would be less than $15/kA-m (26).

The survey conducted under this study elicited considerable information and comment regarding transformers and the potential market for HTS transformers. Sam Mehta, Nicola Aversa, and Michael Walker, writing in the July 1997 issue of IEEE Spectrum magazine pointed out that utilities and industry experts view HTS transformers as a "breakthrough" technology coming at a very "opportune time" (25). These authors note that the use of HTS windings may "soon turn power transformers into compact high-performers on good terms with the environment."

Presently seen HTS advantages include overload without loss of equipment life, lighter and smaller footprint, no need for expensive and environmentally risky oils, and the potential for indoor siting without unnecessary hazard (27).

Transformer reliability is essential. Rochester Gas and Electric sees a number of key parameters for commercial acceptance, including 2X overload capability with no loss of life, ½ size and weight, minimal deliveries of refrigerant (liquid nitrogen), no increase in maintenance personnel, system compatible with existing protection, no failures or long-term maintenance outages, "through fault" capability, ability to support automatic reclosing, and ease of load tap changing (5).

Perhaps the biggest advantage of HTS transformers, according to Mehta, Aversa, and Walker, is their capability for over-capacity operation. Teams from the U.S., Europe, and Japan are working on moving these transformers closer to commercialization.

In order to make the market penetration analysis as credible as possible, a survey of electrical utility engineers and operating people was undertaken. This is described in detail in Appendix III. It is helpful to the analysis to highlight some of the survey results at this point.

Don Fagnan of PECO noted that some of his company's equipment is becoming increasingly ancient, leading him to note that:

> "Even a 20-percent increase [in price of an HTS transformer] may be justified because of savings in other areas. For example, we have 100-year-old cables and 70-year-old equipment at some of our stations. In the more crowded city conditions, HTS equipment may be the key."

However, there was no general consensus across the utilities whether HTS technology would be appropriate for their particular companies. Even when expressing support for HTS transformers, utility engineers qualified their support with warnings that the technology had better be cost-efficient and demonstrably superior to conventional technologies. Concerns were expressed over reliability and the necessity to maintain the coolant at all times.

Despite overall ambivalence about the application of HTS transformers into today's utilities, certain opportunities became apparent during the course of our interviews. For example, when asked if his company was considering future installation of new transformers, Jim Sandborne of PG&E said that he felt power transformers represented the best potential path of opportunity for HTS technologies. He then commented that in his opinion, utilities will become even more conservative with the advent of deregulation, "though that's the wrong thing." He said that this conservatism would cause some companies to fail due to their inability to adapt to new technologies.

Clearly, Sandborne's positive comments, coming from one of the nation's largest utilities in a state pioneering industry restructuring, give rise to the hope that the competitive market will compel other utilities to consider adopting new technologies as a way of remaining competitive.

The salutary environmental and fire-reduction benefits of HTS transformers should be a key point in any outreach effort to the general public, since these transformers would not carry the same risk to the public as conventional ones. From our utility discussions, it appeared as though utility engineers were accustomed to the routine dangers of transformer explosions and fires, taking the appropriate steps to protect public safety. However, HTS transformers would preclude many of these safety procedures and the authors believe this feature could be an important selling point among consumers, if not among utility engineers and purchasing agents as well.

In a follow-up survey, we asked respondents "If HTS transformers became commercially available and were offered to your utility, how would you rank the following criteria in considering their purchase?" The top concern was manufacturer's warranty, echoing the many comments about warranties that we heard during the course of the initial market assessment surveys. The next-highest concern was track record of this technology. Again, this reflects thinking heard repeatedly throughout the course of our initial surveys. It is also somewhat reflective of utilities' traditional reluctance to purchase new and unproven technologies until a track record has been established, a factor inhibiting rapid adoption of innovations.

A final question on the follow-up survey asked whether the "dual capacity of HTS transformers to limit fault currents as well as provide improved transformer performance" would cause respondents to be more favorably inclined to purchase HTS technology. Out of nine who answered this question, eight agreed. Six of the nine said they would be willing to pay more for this capability, but only two provided a specific number (both said, "15%"). The others replied that it depends on various factors, including avoided cost, space considerations, competitive market conditions, specific application, total project costs, and life-cycle costs and savings.

The results of this follow-up survey show conclusively the necessity of a multi-unit field demonstration in starting the market penetration process. It is also important not to discount the importance of aggressively promoting HTS technologies, both to utilities and to electricity consumers, and to electricity research and development organizations throughout the country.

If utility acceptance of HTS transformer technology can be "pulled" by consumer demand, and "pushed" by various research programs, pilot projects and the impetus of international competition and utility deregulation, then HTS transformers have a real chance at breaking out of the laboratory and entering the marketplace.

TECHNOLOGY STATUS

The DOE SPI transformer development program has two teams concurrently pursuing this technology. One team consists of Waukesha Electric (transformer manufacturer), IGC Superpower (wire manufacturer), Southern California Edison (utility end user), Oak Ridge National Laboratory, and Air Products and Chemicals. The second team consists of ABB Power T&D Company, Inc. (systems studies and benefits quantification), American Superconductor (wire manufacturer and current limiting capability), Air Products and Chemicals, Inc. (liquid nitrogen delivery and infrastructure), American Electric Power (utility), Southern California Edison (user utility), and Los Alamos National Laboratory.

The objective of the Waukesha/IGC-SuperPower Superconductivity project is to demonstrate the technical and economic feasibility of HTS transformers of medium (30MVA) to larger ratings. An alpha prototype 5/10 MVA, 3 phase, HTS transformer, with primary/secondary voltage ratings of 24.9/4.2 kV (ac) and 100 kV BIL has been fabricated and is planned to operate long term, supplying power from the local utility grid to the Waukesha main plant in Waukesha, Wisconsin. The unit is using newly developed, high-capacity, single-stage cryocoolers. It is designed to maintain superconducting operation through a 10X fault current (18).

Waukesha continues to expand its manufacturing capability, including capacity to manufacture HTS transformers (29). In September of 2001, Waukesha, IGC-Superpower, and ORNL announced that they were beginning a project to build a 30 MVA transformer, much closer to a large market segment (18), an effort, again co-funded by the DOE. Current 30 MVA transformers cost about $500,000 per copy, and Waukesha believes that a market entry at $750,000 for a superconducting option would be commercially viable. The first multi-unit insertion into the field is likely to occur by 2003. Looking at the Japanese and European efforts, their multi-unit field testing is likely to occur in the same general time period. Therefore, 10% market share is projected to occur by 2010. Should this be accomplished, then based on the aforementioned assumptions, and consistent with the BL&A predictions, 50% market share will be achieved by 2015.

The Waukesha program is on schedule for the development, test, and demonstration of a 30/60MVA Beta prototype design, construction, and test. In 2002, a 5/10MVA unit is scheduled to operate on the grid. This program is also on schedule.

The ABB design includes fault current limiting. The ABB team continues to carry out studies and analysis of transformer markets and potential product designs. ABB has previously designed, built, and operated an HTS transformer on a 630 kVA three-phase utility grid in Geneva, Switzerland. The present team intended to build, test, and install in utility service a 10-MVA, 69-kV/16-kV HTS transformer to be operational in the June 2001 time period (30). A 100-MVA design will also be carried out. The later product will be cooled with liquid nitrogen, weighing substantially less than conventional transformers, and requiring no oil.

According to Mehta et al. (25), Japan and Europe are somewhat ahead of the U.S. in transformer development. As mentioned earlier in the report, the Japanese team (Kyushu University, Fuji Electric, and Sumitomo Electric Industries) is conducting a demonstration using a laboratory-type 500-kVA, 6.6-kV/3.3-kV transformer made from BSCCO-2223 powder-in-tube conductors (HTS wire) operating in liquid nitrogen. The European team of Asea Brown Boveri (ABB), American Superconductor Corporation, Electricité de France, Services Industriels de Genève, and the École Polytechnique de Lausanne, in March 2000, connected the world's first operational HTS distribution transformer now powering the supply network of the city of Geneva.

In Japan (31), a local consortium that centers around the Kyushu University Superconductivity Science Research Center (Kazuo Funagi, Director) is near actual-system testing of a superconducting transformer that operates with liquid-nitrogen cooling at a temperature of 77 K. Conducting overcurrent-overvoltage-resistance tests with a mock-up coil made of a superconducting wire material with the same conductor structure as the actual transformer resulted in no loss of conductor characteristics. The consortium planned to make the transformer and then conduct joint tests of it, beginning in May 2000, which would be the first such tests in Japan. Testing is being accomplished with Kyushu Electric Power Company. This superconducting transformer has a capacity of 500 kW, a primary-side voltage of 22 kV, and a secondary-side voltage of 6.9 kV. In addition, in tests conducted by Kyushu University Professor M. Hara's research office, researchers confirmed lightning-impulse handling characteristics up to a voltage of 150 kV, corona-free insulating characteristics for an alternating-current overvoltage up to 40 kV, and insulating characteristics for an alternating-current overvoltage of 50 kV. The first targets for commercializing the superconducting transformer are the power distribution transformers installed in urban underground substations.

MARKET PENETRATION

The target market for HTS technology in the early years is assumed to be 50% of the total market, since it is the larger sizes where the logistics of refrigeration are more easily handled and will be a smaller percentage of the total costs. The total market consists of 2.5% growth plus replacements. The average transformer lifetime is estimated to be 30 years. Therefore, including new capacity and replacements, the average total transformer sales per year, is estimated to be 5.8% of the total installed MVA. From the foregoing discussion, total transformer installed capacity is approximately 3 times total generation capacity, or 818,500 (2000) multiplied by 3 equals 2,455,500 MVA (2000). The target market to be addressed by HTS equipment, then, is 50% of this amount multiplied by the annual sales rate (5.8%) equaling 71,209 MVA per year based on 2000 generation capability. Consistent with the estimates of Mehta et al. (25), this is the equivalent of approximately 2374, 30-MVA transformers. This target market, then, grows synchronously from 2000 with the assumed growth rate (2.5%), as does the total market.

As mentioned earlier, power transformers are assumed to be responsible for 25% of the losses in the transmission/distribution system. The total loss in this system is assumed to be 6.23% of total generation (Table Mkt-2). HTS transformers will save 50% of the presently wasted electricity in standard transformers. Therefore, the savings for each percent of total market penetration will be:

(HTS penetration percent) × (total annual generation) × (6.23%) × (25%) × (50%) × (5.8% of installed transformer capacity).

The projected HTS transformer market penetration and associated benefits are described in the following table:

Table T-1: Market Projections and Benefits for Transformers - Total Market is 3 X Capability X 5.8%
Generation and End Use Growth Assumed to be 2.5% per year.
Average T&D Loss is 6.23%. Year 2000 numbers are actual.

Year	Electric Capability (M-kW)	Electric Generation (B-kWhr)	Avg Retail Cost Cents/kWhr (EIA Projection)	% HTS Penetration of Total Market	Each Year Savings (B-kWhr)	Each Year Savings ($M)	Annual Savings ($M)	Each Year HTS Sales (MVA)
2000	818.5	3792	6.3	0	0.000	0.00	0.00	0
2001	839	3887	6.9	0	0.000	0.00	0.00	0
2002	859.9	3984	6.8	0	0.000	0.00	0.00	0
2003	881.4	4084	6.7	0	0.000	0.00	0.00	0
2004	903.5	4186	6.6	0	0.000	0.00	0.00	0
2005	926.1	4290	6.5	1	0.019	1.26	1.26	1611
2006	949.2	4398	6.4	2	0.040	2.54	3.80	3303
2007	972.9	4507	6.3	3	0.061	3.85	7.65	5079
2008	997.3	4620	6.3	5	0.104	6.57	14.22	8677
2009	1022	4736	6.3	7	0.150	9.43	23.66	12448
2010	1048	4854	6.3	10	0.219	13.81	37.47	18235
2011	1074	4975	6.3	15	0.337	21.23	58.70	28031
2012	1101	5100	6.3	22	0.507	31.93	90.63	42146
2013	1128	5227	6.3	31	0.732	46.11	136.74	60844
2014	1157	5358	6.3	40	0.968	60.99	197.73	80527
2015	1185	5492	6.3	50	1.240	78.14	275.86	103095
2016	1215	5629	6.4	59	1.500	96.00	371.87	124732
2017	1245	5770	6.4	66	1.720	110.08	481.95	142976
2018	1277	5914	6.5	71	1.897	123.28	605.23	157761
2019	1309	6062	6.5	74	2.026	131.70	736.93	168547
2020	1341	6214	6.6	76	2.133	140.78	877.71	177334

Therefore, by 2010, a total accumulated benefit of $88.06 million should occur from the commercialization of HTS transformers according to present projections. By 2015, this grows to $848 million, and by 2020, to $3.921 billion.

GENERATORS

THE MARKET

The market for generators encompasses many shapes and sizes, from small, portable equipment in the 1 kW range, up to the large, stationary sized equipment used in base load nuclear plants, in the 1-GW range. For the purpose of this study, only the larger, stationary, base load, utility sized generators are considered to be a potential market. With the dramatic marketplace changes and a higher percentage of nonutility generation, the overall market is the growing electric generation industry, which was 818,500 MW (4) in 2000. From Table (Mkt-1) and EIA data, utility and nonutility power generated in that year was 3792 billion kWhr at a value of $228 billion. Again, this market is assumed to grow at the rate of 2.5% per year.

Generators in the class addressed are assumed to be 98% efficient and to have a lifetime of 50 years. This actually exceeds the expected lifetime of a large coal or nuclear power plant, so the replacement market is virtually nonexistent. The maintenance market is a possible target. When a generator of this size goes bad, rarely is the entire unit replaced. Normally, replacement of the bearings, the rotor, and (potentially) the shaft constitute generator repair, so that the replacement rotor market is a possible target. GE produces 10-20 replacement rotors per year and 120-150 (average 135) generators per year in sizes 25-1650 MVA. GE assumes that the HTS near-term potential is (worldwide) 100 units per year plus unit upgrades, and 30-40 rotors per year (32). The GE rotor assumption obviously takes into account the efficiency advantage of an HTS rotor, with early the prospect of replacement a desirable by some segment of the market. Going by the GE assumption, the ultimate worldwide market for HTS capture is 74% (100/135) of the new utility generator market and 200% of the present rotor replacement market.

In a report by Donn Forbes and Richard Blaugher (33), survey results of utility decision makers indicated that “2-5 years of field testing would be required before commercial introduction.” This is consistent with the market penetration assumptions being employed in this present study. In the Forbes/Blaugher study, however, there were wide ranges of predictions as to years from commercial introduction to maximum market share (3-35), and the final percentage share (2%-100%). However, a number of the respondents stated that “cryogenic cooling is acceptable if the reliability is high enough.” Another report by Blaugher (34) states, “At first sight, the expected 1% or so increase in efficiency for the SC machine should cut a utility’s annual fuel costs so much over the customer 40-year lifetime that the savings would almost completely offset the generator’s initial cost.” However, the reliability and maintainability of the HTS machine and the conventional machine need to be identical or favoring the HTS machine, as well, for the HTS equipment to be attractive.

In the two prior editions of this report, generators were not seen as an early entry into the marketplace. In fact, they were seen as dead last, by a lot of years. However, a new, aggressive player has joined the effort: General Electric and American Superconductor have teamed up to pursue the creation and production of advanced generator products. Total funding for the DOE, Superconducting Partnership Initiative project is expected to be $26 million, with DOE providing $12 million over 3-1/2 years. The GE press release on the subject uses the phrase "potential for competitive cost, high reliability, and rapid market introduction and a high probability of acceptance by the power industry." The first item to be built will be a 100MW power generator based on BSCCO wire technology (18, 35).

TECHNOLOGY STATUS

From earlier assumptions, commercial HTS utility generators can save 1% of total generated electricity wherever they are installed.

Prior to the recent entry of General Electric, Japan had placed the development of superconducting generators as a higher priority option than manufacturers and the DOE in the U.S. The following information is from the magazine, "Tokyo Energy":

> "Measures are being pushed forward to expand the scope and increase the number of power plants and power transmission and transformer facilities to cope with the demand for electric power, which continues to increase, in Japan, even in times of idle economic growth. But the creation of large capacity electric power sources, and the means for transmitting this power over long distances has given rise to problems of securing sites for the construction of power transmission lines, and ensuring the stability of power systems. There is also the need to further reduce power loss, and to reduce the burden on the environment, such as curbing global warming gas emissions. The most promising means of coping with these kinds of problems lies in superconductor technology (36)."

The Engineering Research Association for Superconductive Generation Equipment and Materials (Super-GM), as part of the New Sunshine Program run by the Agency of Industrial Science and Technology (AIST) of the Ministry of International Trade and Industry (MITI), has been entrusted by the New Energy and Industrial Technology Development Organization (NEDO) to conduct research and development (R&D) work on a superconducting generator and related equipment and materials, which will serve as forerunners in the application of superconducting technology in the field of electric power. Verification testing is currently being carried out with the Kansai Electric Power Company (KEPCO), on a 70,000 kW-class model generator.

The team members include Hitachi, Mitsubishi Electric, and Toshiba. Last year, this program began the final stage of testing the 70 MW superconducting generator with three different rotors, each constructed by a different team member. The next phase will be the design and construction of a 200 MW class generator, seen as a commercial "pilot."

On February 3, 1998, Nikkei English News reported, through the Nikkei America web site, that "Hitachi Ltd. has taken a big step toward commercialization of superconducting power generators with a successful test of a prototype 70,000-kW class generator. The world's first successful testing has raised hopes for commercial superconducting power generators as early as in 2010." And further, "The prototype, set up at Kansai Electric Power Co.'s Osaka plant, has recorded a power output of 79,000 kW, the highest ever for a superconducting power generator, in mid-November." Finally, "After the trials, the prototype will be tested with its generation capacity raised to 200,000 kW." The article points out that this is a lower temperature technology item (LTS) cooled with liquid helium.

The Nikkei article additionally points out that "In the case of a 1,000,000 kW class superconducting power generator, it is likely to measure around half (the size) of a typical comparable power generator with a length of 8 meters and a weight of 400 metric tons."

The generator efforts in both the U.S. and Japan appear to be behind the electric motor efforts in terms of time and planned accomplishments. By the same token, motor and generator technologies are similar enough that successes in the motor field could rapidly cause acceleration in the generator efforts. Also, demonstrated success in the Japanese program could rapidly accelerate U.S. interest.

MARKET PENETRATION

In terms of percentage of ultimate market, HTS generator production and sales are assumed to proceed on the same track as electric motors, but behind HTS electric motor market penetration. Based on the foregoing data, this would appear to be a reasonable assumption.

Conversations with Jim Bray, program manager at General Electric, have indicated that the company is seriously and aggressively pursuing the generator option. Therefore, the multi-unit test of generator technology is expected to begin in 2008, with 10% market penetration by 2014, followed by 50% of the market by 2019. This would appear to be consistent with the potential as described by GE and the description of the Japanese efforts, and it shortens by two years the date of market introduction estimated in the prior "Products and Benefits" reports.

In the limit (2000 values), fully installed HTS generators (utility and nonutility) would save $2.61 billion per year (1% of total generation) based on numbers for 2000. The annual sales market, from our list of assumptions, is assumed to be 2.5% growth + 2% replacement (50-year life) or 4.5% of total electric industry capacity annually. This equates to 4.5% × 818,500 MW or 36,832 MW annually based on 2000 numbers. Per sales year, implemented, retail value, electric savings become:

(4.5%) × ($2.61B) × ([1.025]n) × (% market penetration) × (% change in electric costs)

The market penetration expected and associated benefits are expressed in the following table:

Table G-1: Market Projections and Benefits for HTS Generators
Generation and End Use Growth Assumed to be 2.5% per year.
Year 2000 numbers are actual.

Year	Electric Capability (M-kW)	Electric Generation (B-kWhr)	Avg Retail Cost Cents/kWhr (EIA Projection)	Market Penetration (%)	HTS Sales (MW)	Each Year Savings (B-kWhr)	Annual Savings (B-kWhr)	Annual Savings ($M)
2000	818.5	3792	6.3	0	0	0.000	0.000	0.00
2001	839.0	3887	6.9	0	0	0.000	0.000	0.00
2002	859.9	3984	6.8	0	0	0.000	0.000	0.00
2003	881.4	4084	6.7	0	0	0.000	0.000	0.00
2004	903.5	4186	6.6	0	0	0.000	0.000	0.00
2005	926.1	4290	6.5	0	0	0.000	0.000	0.00
2006	949.2	4398	6.4	0	0	0.000	0.000	0.00
2007	972.9	4507	6.3	0	0	0.000	0.000	0.00
2008	997.3	4620	6.3	0	0	0.000	0.000	0.00
2009	1022	4736	6.3	1	460	0.021	0.021	1.34
2010	1048	4854	6.3	2	943	0.044	0.065	4.09
2011	1074	4975	6.3	3	1450	0.067	0.132	8.33
2012	1101	5100	6.3	5	2477	0.115	0.247	15.56
2013	1128	5227	6.3	7	3553	0.165	0.412	25.93
2014	1157	5358	6.3	10	5206	0.241	0.653	41.12
2015	1185	5492	6.3	15	7999	0.371	1.023	64.47
2016	1215	5629	6.4	22	12029	0.557	1.581	101.16
2017	1245	5770	6.4	31	17368	0.805	2.386	152.68
2018	1277	5914	6.5	40	22986	1.065	3.450	224.26
2019	1309	6062	6.5	50	29453	1.364	4.814	312.91
2020	1341	6214	6.6	59	35604	1.650	6.464	426.61

Although the monetary benefits from generators are less than those from motors or transformers, they are clearly cumulatively significant at $1378 billion by 2020.

UNDERGROUND POWER CABLES

THE MARKET

The market for underground power cables is relatively less complex than that for other potential herein previously described HTS products. From the Appendix I facts and assumptions and associated published studies, we know the total amount of installed, underground cable in the U.S. and much about the HTS cable market potential. In 1995, there were 3580 miles of underground transmission cable in the U.S. The market in that year for U.S. sales was 158 miles. Growth in the total number was 140 miles (37). The annual growth rate in the cable market for HTS cable is expected to be 3.4% per year (38). A cable demonstration project of at least 4 years will be required (38). HTS cable with life-cycle costs equal to conventional cable and with twice the ampacity would capture 56% of the underground transmission market 10 years after the first commercial sale (38). HTS underground cable savings can reach 125,000 kWhr per mile per year, or based on 6.89 cents per kWhr, a monetary savings of $8612.50 per mile per year. This is equivalent to saving ½ the presently lost power in underground cables (32).

Current estimates indicate that approximately 2200 miles of existing underground cable are approaching the end of their service life and are eligible for replacement with HTS cable (30). The Pirelli HTS cable is specifically designed as a replacement for in-place underground cables, upgrading capacity substantially without additional rights-of-way or conduits. The replacement HTS cable is expected to be able to carry 3-5 times the power of conventional cables in the same cross-section (39).

In a report for the Department of Energy, Energetics, Inc. states that 3500 miles of underground transmission cable exists, of which 60% is nearing the end of its useful life. Energetics anticipates that commercially available HTS cable should be ready for replacement of underground transmission cable in the 2004-2006 time period (40).

The main drivers for the HTS market are urban space constraints, right-of-way difficulties, and new tunneling requirements (30 meters deep in London and Berlin), coupled with increased urban demand for electrical service (41). Some key early market examples are France (225 KV), Detroit (24 KV), and London (11 KV). The trade-off is seen as the additional cost of HTS cable versus the even greater cost of deep tunneling and right-of-way acquisition.

The key milestone, then, is to get to the point where HTS cable, with life-cycle costs equal to conventional cable, and with twice the ampacity, has been demonstrated for at least four years, in multiple units and in multiple utilities. When the demonstration time is complete and results are positive, commercial introduction can begin, following the path previously described. Southwire anticipates that a commercial HTS cable could reach the market by 2005 (40).

TECHNOLOGY STATUS

There are two cable teams actively participating in the U.S. Superconductivity Partnership Initiative. The first team is led by Southwire Company (systems manufacturer) and includes Argonne National Laboratory, Oak Ridge National Laboratory, Plastronics, Inc. (subsidiary of EURUS Technologies, Inc.), and IGC - Superpower (HTS tape development), Georgia Transmission (electrical systems design), and Southern Company. The second team is led by Pirelli Cables and Systems (systems manufacturer), and contains American Superconductor (wire manufacturer), Lotopro (refrigeration systems), Detroit Edison (host utility), the Electric Power Research Institute, and Los Alamos National Laboratory. Additionally, in Europe, a cable commercialization group has formed, led by the Danish firm DTU.

Pirelli presently has 50% of the United Kingdom market, and a dominant presence in Europe. Their present cable is paper insulated and oil filled, presenting environmental risks. Pirelli feels that the first commercial applications of HTS cable will be niche applications that require high amperage and only medium to high voltage, which are the optimum characteristics for HTS cables (41). Pirelli envisions early implementation/commercialization of HTS cables by the 2005 time period.

The following table shows HTS Cable Demonstration projects currently underway:

Table C1: Current HTS Cable Demonstration Projects (42)

Participants	**Voltage (KV)**	**Current (KA)**	**Cable Length (Meters)**
EPRI, Pirelli, DOE	115	2	50
DOE, IGC, Southwire	12	1.25	5
Tokyo Electric Power, Sumitomo	66	1	30
Electricité de France, Pirelli	225	3	50
Pirelli, Siemens	110	2	50
NKT Cables, Nordic Superconductor Technologies A/S, Danmarks Tekniske Universitet, and other Companies and Utilities	60	2	30
ENEL SpA, Pirelli, Edison SpA	132	3	30
EPRI, Pirelli, DOE, Detroit Edison	24	2.4	120
Southwire, DOE, ORNL	12.5	1.25	30

From the preceding table, it is abundantly clear that multi-unit field tests in utility environments are well underway.

The Detroit Edison Frisbie substation is the site of the first installation and demonstration of an underground HTS cable in a U.S. utility network. Three 400-foot cables were installed inside 4-inch-diameter underground ducts during the summer of 2001 by the Pirelli/Detroit Edison team. All other cable components, including the cryogenic system, were completed in the fall of 2001 (43). Participants in the Detroit Edison Superconducting Cable Demonstration project reported on January 16 that the project is experiencing a delay in completion. In a statement, Pirelli Power Cables and Systems said that it does not expect commissioning of the system to be completed before the second half of 2002. Pirelli added, though, that it is "anticipated that the data resulting from the tests will provide a clear picture of the situation and enable the creation of a new time schedule during the second quarter of 2002 (43)."

Pirelli notes that "[i]n response to low vacuum levels observed in two of the cryostats of the HTS cable system, Pirelli conducted preliminary tests which confirmed the presence of vacuum leaks. All of the system components had been qualified at the factory before shipping and were assembled in the field." Pirelli adds that it is "carrying out systematic tests to locate the origin of the problem and is developing procedures to fix several different potential sources of leaks….The customers served by the Frisbie station will not be affected, since the site for this research program was selected partly because of the availability of parallel paths for power delivery, maintaining Detroit Edison's design standards for reliability and redundancy (43).

Last May, Copenhagen beat Detroit to the punch by "energizing" the first HTS cable in a utility grid. A 30-meter cable from Denmark's NKT Group now provides electricity to 150,000 residents served by Copenhagen Energy. Some Paris customers of Electricité de France are slated to get power from a similar HTS project this year.

Also in May, Tokyo Electric Power Co. turned on its third HTS project, using 100 meters of cable from Sumitomo Electric Industries Ltd., and the utility is planning a 300-meter operation for 2005. A group led by Pirelli Cables & Systems and KeySpan-Long Island Power Authority is designing by far the longest installation anywhere, 800 meters. It is due online in 2004. And next year could see the start of two more urban tests - one by Edison of Milan, Italy, and another in Columbus, Ohio (19).

Detroit is just one example of the significant progress in HTS technology over the past two years. Southwire Co. got the ball rolling in January 2000 by switching on the first industrial HTS transmission system at its home base in Carrollton, Ga. For 12,700 continuous hours, three 30-meter-long HTS cables have funneled all the power to the company's three Carrollton factories, with nary a glitch. Southwire made the cables with HTS wire from Intermagnetics General Corp. and technical help from Oak Ridge National Laboratory. The cable is carrying the electricity needed to operate a Southwire manufacturing facility. The cable is rated at 12.4kV, 1,250 Amperes, 3-phase, 60hz, and 27 MVA.

A joint team of Southwire and American Electric Power plans another cable installation. The installation will take place in Columbus, Ohio.

Further, IGC-Superpower has announced that it will be installing a ¼-mile long underground HTS power cable in Albany, New York on the Niagara Mohawk power system. This installation is planned to be outside a substation as a physical part of the grid.

Pirelli has designed and commissioned a dedicated HTS cable manufacturing line (44). This pilot manufacturing plant can readily produce commercially required quantities of HTS cable. Difficulties to be overcome for broad market penetration include customer confidence, proven reliability, and such cost drivers as the cost of the superconducting material, cryostat cost and performance, and installation parameters (41).

In Japan, Tokyo Electric Power Company is working with Sumitomo Electric Industries, Ltd., and Furukawa Cabling System on developing a 6 kV, 1000-MVA HTS cable system, with the ultimate goal of deploying it around Tokyo to meet the city's growing needs (45). In Germany, Siemens is working on "the first serially produced superconducting cable for 110 kilovolt service (to be ready) in late 1998 (46)." The cable will be 50-m long.

Again, the key to market readiness of HTS cables may be utility readiness to accept the vagaries of a new technology, which will be a part and parcel of overall utility reliability. Price drivers are the refrigeration system and the basic cost of the HTS materials. The minimum time to full commercial sales is 3-5 years (47).

HTS cables may make economic sense under city streets. A meter of HTS wire that can carry a 1000-ampere current costs about $200, vs. $4 for copper. Still, that's a fraction of what it cost in 1995--$1000 a meter. American Superconductor says costs will gradually drop to $50 after it kicks off production at its new $85 million factory. The highly automated plant can spew out 20,000 kilometers of HTS wire annually--40 times current output (19).

Because the superconducting cable is compact, the needed conduits for underground transmission lines are commensurately small in size and quantity in comparison to conventional practice. In the Japanese project, existing superconducting wire material (100,000 kW class) with a rectangular profile is used as the conductor. This material has already been used widely in cable manufacturing. Three of these superconductors are assembled and housed in one conduit. The high temperature, superconducting cable system is then completed using liquid nitrogen refrigeration.

If this type of cable becomes commercial practice, power transmission ten times that the present (100,000 kW to 1,000,000 kW) will be possible using existing underground conduits (inner diameter of 150 mm). The Japanese feel that successful development will lead to effective utilization of existing equipment, large reductions in construction costs, and effective use of underground space.

MARKET PENETRATION

It is clear that the prospective manufacturing and distribution teams are now in the process of a multi-unit demonstration. The Pirelli program, the Southwire program, and the Japanese effort are expected to follow similar paths, with equivalent timing of the multi-unit field test and demonstration. As stated above, the utilities require the multi-unit demonstration to continue for four years. Therefore, commercial introduction is expected to occur in 2004, with first sales in 2005, with a market growth rate of 3.4% per year, leading to a 10% market capture by the year 2007. By the year 2014, 56% of the market will be captured.

Total miles sold of HTS cable in any given year will be:

(% Market Penetration) × (158 miles) × ($[1.025]^N$) where "N" is the number of years past 1995. No detailed, cable market information is available beyond 1995.

The cable market is not expected to deliver the same level of dollar benefits as the other foregoing technologies, but the benefits may be more in utility operations than customers' electric bills. Especially in urban environments, population growth and electric demand growth can only be addressed by putting more power down established, underground, T&D corridors. This means more power in the same cross-section may become essential, which is the main benefit that HTS cable will provide in this market.

Forbes (38) carried out a more detailed and extensive analysis, resulting in much of the basic information for this portion of the study.

Table C-2: Underground power cables:
Market penetration and benefits

Underground Power Cables:
Market Penetration and Benefits:

Year	Market Penetration %	Miles Sold This Year	Total Miles Installed	Annual Savings M-kWhr	Annual Savings $M
2004	0	0.00	0	0.00	0.00
2005	3.4	6.87	6.87	0.86	0.06
2006	6.7	13.89	20.76	2.60	0.17
2007	10	21.25	42.01	5.25	0.33
2008	15	32.68	74.69	9.34	0.59
2009	21	46.88	121.57	15.20	0.96
2010	27	61.77	183.34	22.92	1.44
2011	33	77.43	260.77	32.60	2.05
2012	40	96.19	356.96	44.62	2.81
2013	48	118.31	475.27	59.41	3.74
2014	56	141.47	616.74	77.09	4.86
2015	63	163.15	779.89	97.49	6.14
2016	69	183.15	963.04	120.38	7.70
2017	74	201.34	1164.38	145.55	9.32
2018	77	214.73	1379.11	172.39	11.21
2019	79	225.80	1604.91	200.61	13.04
2020	80	234.35	1839.26	229.91	15.17

Total accumulated savings through the year 2020 will be $79.59 million.

FAULT CURRENT LIMITERS

THE MARKET

HTS fault current limiter (FCL) efforts are worldwide. Major efforts are under way with ABB (Switzerland), GEC-Alsthom (France), Tokyo Electric (Japan), Rolls Royce and Merck (United Kingdom), and Siemens (Germany). The desire for HTS FCL products is substantially greater in Europe than in the U.S. (5).

The earlier, United States SPI fault current limiter team consisted of General Atomics (systems developer and integrator), Southern California Edison (utility end user), IGC-Superpower (wire manufacturer), and Los Alamos National Laboratory (LANL). The present effort is located at LANL.

Utility benefits from this new product concept include increased safety, reliability, and power quality. Utilities can reduce or eliminate the cost of circuit breakers and fuses by installing HTS current controllers. Fault currents in transformers, for instance, can run 10-20 times the steady state design current. The HTS FCL can reduce these fault currents to levels not exceeding 3-5 times the steady state current, protecting and extending the life of transformers and associated utility equipment (48).

FCLs represent a new class of electrical equipment, expected to generate a whole new market. At present, there is no established market for this equipment to penetrate; however, if it can be shown that the expense to purchase, install, and maintain this kind of equipment can be offset by savings over the lifetime of other installed equipment (such as transformers), then a significant market may be quick to develop. Eddie Leung, writing in the July 1997 issue of IEEE Spectrum, describes the situation as follows:

> "Sudden reductions in the impedance of power grids (such as after lightning strikes) will lead to a surge of current, termed a fault current. This causes circuit breakers to open, then close. If the fault condition persists, the circuit breaker will remain open and repair crews will be summoned. Until the power is restored, an outage occurs. This means that in today's electricity-dependent economy, significant hardship and economic losses can occur during such outages (48)."

An ideal FCL would have zero impedance throughout normal operation; provide sufficiently large impedance under fault conditions; provide rapid detection and initiation of limiting action (within less than one cycle, or 16 ms); provide immediate (within a half-cycle, or 8 ms) recovery to normal operation after the clearing of a fault; be capable of addressing two faults within a period of 15 s; and be compact, lightweight, inexpensive, fully automatic, and highly reliable with a long lifetime (49).

Leung points out that "new superconductors are well-suited for fault-current limiters, thanks to their stable thermal properties [and] higher operating temperatures." As he notes: "[Conventional circuit] breakers are expensive, have limited lifetimes, and cannot interrupt fault currents until the first fault zero. High-impedance transformers, with their high losses, breed inefficiency in a system. Fuses have too low a withstand fault current and have to be replaced manually. Air-core reactors, although a proven approach, are subject to large voltage drops, incur substantial power loss during normal operation, and require installation of capacitors for volt-ampere reactive (VAR) compensation. System configuration naturally reduces system reliability and its operational flexibility, besides adding to costs (49)."

The solution, Leung points out, is a new line of superconducting utility devices, including an "HTS current controller that can perform current control, fault-current limiting and fast-circuit-breaking, [which] will become viable with the inevitable advances of HTS, cryocooler, and power electronics technologies." He writes that "the realization of a practical and cost-efficient fault-current limiter is within reach and the world's leading electrical equipment manufacturers are racing to introduce a commercial unit (49)."

Taylor Moore supports Leung's assertions. "Superconducting fault current limiters could afford utility equipment greater protection against large momentary power spikes caused by short circuits or lightning. Moreover, such devices could provide utilities a way to interconnect parts of distribution systems more tightly and to manage power flows more effectively with less redundancy of protective equipment and substation capacity (50)."

Overall, based on our utility discussions, FCLs appear to enjoy some of the greatest support of the various HTS technologies by engineers and the purchasing decision makers. Even those who were not initially aware of FCLs seemed to evaluate the technology highly.

Acceptance of FCLs appears to be aided by the fact that they are among the most advanced of the HTS technologies in terms of development and market readiness. Furthermore, they fill a need not readily addressed by conventional technologies. Finally, due to their trailblazing applications, they can be justified to investors and regulators in a clear and straightforward manner, offering demonstrable advantages over conventional technologies.

TECHNOLOGY STATUS

A 2.4-kV HTS FCL was successfully tested in September 1995 at a Southern California Substation where it successfully reduced a 3.03 kA fault current, performing 37% above specifications. A 15-kV FCL was then tested at a substation on the Southern California Edison grid where problems occurred, ostensibly due to high voltage shorts.

The Superconductivity Partnership Initiative in this area is now defunct, and LANL has retrieved the prototype unit that was built by General Atomics and is restoring the unit.

Voltage breakdowns had occurred on this unit while it was under test at the Southern California Edison substation at Norwalk, CA on a 12.5 kV bus.

The two HTS coils that had experienced high currents through the terminals during the field testing revealed HV breakdown through the electrical insulation at the same location in each coil (51). After restoration of the unit, testing, including load tests and short circuit tests at reduced current levels, will be conducted.

Although the US effort seems to be stalled at this point, ABB, in Europe, continues to move forward with a 6.4MVA Fault Current Limiter design. ABB reports a prototype unit now operating under test.

Presently, the cost of these systems is still “prohibitive” (52), the cost drivers being the superconducting material (wires) and the refrigeration systems. Cryocooler cost and reliability are key, since these systems will operate in the range of 40 K. BSCCO wire cost is coming down; however, the FCL team feels that, for widespread use, this cost must come down to $1/kA-m, and not even the $10/kA-m present goal will suffice. Also, the present wire is too thick and tough to bend, making the application difficult at best (52). It is felt that 77 K operation (liquid nitrogen temperature), using second generation wires or tapes, will be key to commercial success (52).

Utility acceptance will take considerable time and, therefore, demonstrations of the capabilities of this type of new equipment will be essential to marketplace success. Three teams are presently addressing this technology, GEC-Alsthom/Electricité de France in France, ; Siemens and Hydro-Quebec in Canada, ; and Toshiba and Tokyo Electric in Japan.

MARKET PENETRATION

The present status of the equipment is the completion of construction and test of “precommercial” items. In this scenario, consistent with our prior market entry assumptions, 10% market share should be achieved by 2008, and 50% share would be achieved in 2013.

THE BENEFITS

The benefits of FCLs cannot be measured in terms of energy saved leading to dollars saved because their benefits are operational rather than efficiency based. Their market growth will likely occur as utilities see their operational advantages offsetting what would otherwise be equipment replacement costs. Some authors and some HTS experts suggest that HTS FCLs and HTS transformers may well be sold together or in an integrated design because of the inherent benefits of this configuration. Since the main advantages of HTS FCLs are tied to the protection of other utility equipment and customer service, the integration of the concept with the main piece of equipment it will protect is a rational engineering procedure. In any event, it will be interesting to watch this new market develop and grow.

TOTAL MARKET BENEFITS

The results of the analysis have been accumulated, for all products, in the following table. The projected benefits, based on this conservative study, are substantial, but occur in a time frame, which warrants considerable, and continuing, Federal funding and involvement. This is the classic "high-risk, high-payoff" scenario on which there is general agreement that Government has a justified role. It is up to the technology community and the potential manufacturers and suppliers to carry out the development and product introduction process successfully.

Totals Table - Based on 2.5% annual growth in capacity and generation. Annual benefits in $ Million).

Total, Annual, Benefits as a Function of Time ($ Million):

Year	Motors	Transformers	Generators	Cable	Total	Cumulative
2004	0	0.00	0	0.00	0.00	0
2005	0	1.26	0	0.06	1.32	1.32
2006	0	3.80	0	0.17	3.97	5.29
2007	0	7.65	0	0.33	7.98	13.27
2008	27.29	14.22	0	0.59	42.10	55.37
2009	83.24	23.66	1.34	0.96	109.20	164.57
2010	169.24	37.47	4.09	1.44	212.24	376.81
2011	316.18	58.70	8.33	2.05	385.26	762.07
2012	527.03	90.63	15.56	2.81	636.03	1398.1
2013	835.76	136.74	25.93	3.74	1002.17	2400.27
2014	1310.49	197.73	41.12	4.86	1554.20	3954.47
2015	2024.11	275.86	64.47	6.14	2370.58	6325.05
2016	3103.37	371.87	101.16	7.70	3584.10	9909.15
2017	4488.07	481.95	152.68	9.32	5132.02	15041.17
2018	6360.31	605.23	224.26	11.21	7201.01	22242.18
2019	8576.67	736.93	312.91	13.04	9639.55	31881.73
2020	11322.83	877.71	426.61	15.17	12642.32	44524.05

By the end of year 2010, benefits are projected to accrue to a total of $377 million. By the end of 2015, total accrued benefits become $6.325 billion and, by 2020, the accrued benefit is $44.5 billion.

TECHNOLOGY CONSTRAINTS TO COMMERCIALIZATION

The two main constraints to commercialization, consistently expressed by systems developers, are the cost of the superconducting material itself, and the cost and complexity of the required refrigeration systems. Second generation wire now under development will hopefully help alleviate both of these technology constraints, as second generation wire is thought to have considerable cost advantages in terms of dollars per kA-meter; it also requires more easily obtained temperatures of liquid nitrogen versus the helium cryocoolers necessitated by first generation technology. What follows is a discussion of the status of efforts in both of these areas.

WIRE COST AND TECHNOLOGY - SECOND GENERATION TAPE

Second generation HTS wire, or "tape," is generally agreed to be critical to the broad, successful introduction of HTS products and the attainment of their projected benefits. The tape holds the promise of the needed combination of higher performance at the temperature of liquid nitrogen, and lower cost in terms of $/kA-meter. Based on original work conducted at LANL and ORNL, a number of private sector technology developers and potential manufacturers are now aggressively pursuing the development of this requisite option.

Energetics Corporation, a subsidiary of VSE and long time support contractor to the Department of Energy Superconductivity Program has provided the main support for the DOE/ORNL Coated Conductor Technology Development Roadmap. The Roadmapping Workshop was held on January 18-19, 2001, and contained experts from utilities, manufacturing companies, materials suppliers, the Department of Energy, Universities, National Laboratories, and other government entities. The vision for the Coated Conductors is:

> "Low-cost, high-performance YBCO Coated Conductors will be available in 2005 in kilometer lengths. For applications in liquid nitrogen, the wire cost will be less than $50/kA-m, while for applications requiring cooling to temperatures of 20-60K, the cost will be less than $30/kA-m. By 2010, the cost-performance ratio will have improved by at least a factor of four (53)."

Numerous potential manufacturers of second generation tape, including IGC-Superpower, 3M, and Fujikura are now reporting continuous production of these tapes in multi meter lengths. Uniformity over these lengths is improving rapidly.

Los Alamos National Laboratory continues excellent work on 2nd generation, YBCO based tapes. In the summer of 2001, they reported tapes at 75 K achieving self field critical current values (Ic) over 100 amperes over 1 meter length tapes. Shorter sections of tape have actually achieved Ic over 200 amperes.

IGC-Superpower, of Latham, N.Y., announced on January 7 that it had achieved what it characterized as a "major milestone for calendar year 2001: continuous production of second-generation high-temperature superconducting (HTS) tapes." The company notes that the second-generation tapes were produced in pilot-scale facilities established at Schenectady, N.Y., a year ago. "Demonstration of continuous, versus batch, production of second-generation HTS material is a critical stepping stone in SuperPower's [IGC subsidiary] goals of achieving longer lengths of high-performance second-generation HTS tapes and ultimately, routine, volume production of this high-performance material," said Philip J. Pellegrino, Intermagnetics' Energy Technology sector president. "We remain on target to achieve our next objective of 100 amp-meter performance in greater than one-meter lengths during calendar 2002 and are now establishing a 2003 target of 1000 amp-meter performance in greater than 10-meter lengths. These targets are consistent with our previous projections to achieve commercial production of second-generation HTS by mid-decade (21)."

Pellegrino noted the second-generation HTS tapes made using the continuous process achieved current density (current per unit cross-sectional area) in excess of one million amperes per square centimeter at liquid-nitrogen temperature. In comparison, a copper wire of the same cross-sectional area carries 1000 to 10,000 times less current. SuperPower has been routinely producing 20-centimeter second-generation HTS tapes and recently produced the first meter-long tape (21).

High-purity silver accounts for about two-thirds of the materials composition of first-generation BSCCO-based superconductors, making them too expensive for practical use. In addition, they are fabricated using a labor-intensive batch process in which the superconducting material is packed into silver tubing, heat-treated and then drawn and rolled in several stages to form HTS tapes. This process also potentially impacts product quality in two ways: in materials consistency and in the increased possibility of operator error.

Second-generation HTS technology, however, is made from less-costly materials using a continuous, highly automated process. These attributes represent major steps toward achieving a cost-benefit ratio favorable enough to make HTS technology commercially viable. Second-generation HTS technology uses inexpensive nickel or stainless steel alloys. Less than 5 percent of the material's composition is silver, which is used only as a protective coating. Using an automated, continuous thin-film deposition process similar to those found in the semiconductor industry, multiple layers of thin films - buffers, the HTS layer itself, and a silver overlayer - are deposited on a flexible metal substrate. This is done in reel-to-reel mode, similar to the way aluminum foil or adhesive tapes are produced (54).

Second-generation HTS conductor is produced using technologies similar to those used in semiconductor industries. Technical challenges in producing second-generation HTS conductor include using substrates of flexible metal tapes instead of rigid wafers and employing a process that could continue for days rather than a batch process that lasts a few hours. In meeting the milestone this year, IGC-SuperPower was able to demonstrate that second-generation technology can indeed be scaled to a continuous pilot-scale operation.

In addition to the dramatically less expensive materials employed in manufacturing second-generation HTS tape, the continuous production method should also reduce labor costs substantially compared with the process used in manufacturing first-generation HTS material. These are viewed as important developments in achieving the cost-benefit ratio critical to making HTS technology commercially viable.

IGC-SuperPower was granted an exclusive license for second-generation HTS process technology from Los Alamos National Lab last year and developed additional technology exclusively with Los Alamos over the past year. The second-generation HTS tapes produced by Los Alamos still hold the world-record for the best performance.

MgB2 is a new and exciting option now considered for second (or third) generation tapes and/or wires. It is being made in long lengths today, however; as of this writing, only short pieces (1 cm) have been tested, and critical current densities for the short pieces are in the range of 10kA/cm2. While interesting, this does not compare favorably (yet) with YBCO results where "1 meter long samples of YBCO wire have ten times this critical current density in nitrogen at 1 Tesla" (53). Also, MgB2 operates in the superconducting mode (today) up to 25K, while YBCO operates at 68K or above. The cost penalty for the needed refrigeration difference is a factor of about three. For these reasons, any affect of MgB2 on the superconducting marketplace is not considered in this analysis. It is simply too early to tell if this new material will really have a positive impact.

IGC-Superpower, in a news release of January 7, 2002, stated, "We remain on target to achieve our next objective of 100 amp-meter performance in greater than one-meter lengths during calendar 2002, and are now establishing a 2003 target of 1000 amp-meter performance in greater than 10-meter lengths (21)."

The DOE Wire Program goals are to create HTS wires able to carry 100 times the power of comparable copper wire - with zero electrical resistance - by 2007; and by 2010, to lower the cost of 1000 amp HTS conductors to $10 per meter (now $300 per meter) (55).

Second generation wire (tape) development also continues in Japan. The Japanese timetable as presented by Los Alamos National Laboratory is:

2003 - 100 meter tapes
2004 - prototype transformers and generators
2005 - commercially useable kilometer length tapes
2006 - market entry for first devices using coated conductors

CRYOGENIC SYSTEMS

Several recent documents have been published that provide a current and comprehensive review of HTS refrigeration system options (56-60). These references present current and projected performance and cost estimates, and the important near- and longer- term technology developments needed to bring these cryogenics systems into technical and cost conformance with the target needs for HTS devices. The following sections highlight and summarize the issues and projected impacts these systems can affect when integrated with their intended HTS device(s).

This overview discusses refrigeration system status as follows:

- Current Situation and Trends
- Economics
- Markets and Timing
- Needs/Goals and Technical Directions

1. Current Situation and Trends

In general, there is a body of professionals who believe that, in order to reduce the currently very high cryocooling equipment costs, HTS devices must be optimized to operate at temperatures of between 60-80K. At this level, open loop LN2 pool boiling and vaporization are effective, simple and economically sensible systems to employ where cable lengths and/or device sizes are small to moderate and the current lead is relatively constant.

For operations where magnetic field losses are inherent (motors, generators, transformers), or in larger scale applications, a hybrid system may provide the variable cooling (current following) by including a parallel-connected closed loop system possibly using pulsed tube or Stirling cycle units, for cooling temperatures lower than 77K and/or to add redundancy to assure critical operation can be sustained. Vacuum assist is another possible solution for supporting lower temperature operations (to 65K).

At this juncture, closed-loop options (pulsed tube, Stirling cycle units) are considered the only options for very large (100s -1000 Wcold) HTS systems. There is limited experience with these cycles as few units have been produced for industrial application; however, their reliability in space settings has been proven though at very high capital costs.

High current carrying HTS cables operating at less than 80K, have three significant thermal loads, that associated with terminations, maintaining the cable cold (for the environment) and the current load. Typically, the static load (termination resistance and cooling to the HTS operating level) is relatively constant and comprises a large portion of the total thermal load on the cable. The dynamic loads are AC and dielectric losses with the latter being relatively small at distributor level voltages (approx. 0.05 W/m-phase); the total loss approximating 1W/m-phase. Because of the configuration differences between cables and the other HTS devices, equivalent cable loads demand larger cooling systems (59). A recent study concluded that the efficiency of the refrigeration cycle is largely determined by the compressor performance, regardless of the selected cycle (60).

2. Economics

Key factors that impact HTS system cost include efficiency and lifetime, availability and equipment complexity/moving parts. The term "availability" is favored over "reliability" because, although related, industrial and utility operations are less tolerant of outages than to provisioning, say, redundancy, to maintain electric service. Thus, the trade-off of dual systems (one as a backup) to as yet unproven single refrigeration systems with limited but promising performance and technical sophistication, must be applied as HTS devices enter their respective markets. Currently available larger scale cryocoolers cooling to 80K operate at about 20% of Carnot efficiency and exhibit costs of $100-150/W. To be effective for HTS applications cryocooler costs must drop to $25/W while simultaneously improving efficiency by 2x to 30% of Carnot. While increased production volume can be effective in reducing cost, R&D effort is required to achieve this level of efficiency improvement.

Table 1 summarizes the situation with respect to cryocooler cost impact on HTS systems and projected market size (56). What is clear from the table is that generators represent an excellent first market opportunity. The cryogenic system cost is low compared to the total generator cost, has a high energy saving payoff, and comprises a major HTS market share. The second most attractive HTS market is cables with the remaining devices placing much lower in the economic and energy savings categories.

Table Cr-1: Cryogenic System Cost (% of total HTS cost) & Energy Savings(56)

HTS Device	Market Entry Year	% of HTS System Cost		% of Energy Savings in	% of HTS Market ($1000)	
		2015	2025		2015	2025
Cables	2007	23	13	31	35.5	32.3
Transformers	2015	20	10	11	negl	21.5
Generators	2009	4	2	54	61.4	37.2
Motors	2009	3.5	3.7	4	3	9

3. Markets and Timing

As indicated in the above table, HTS cables and generators are obvious first targets of market entry opportunities, should the projections for market penetration and overall HTS device demand be reasonable. The major challenge for cryocoolers used in cable applications is to reduce first costs and perfect remote monitoring and control for these units. Current design factors require that these be placed at approximately one-mile intervals to sustain low temperatures for optimum cable performance, thus a large number of cooling units for each transmission line. Hence, the high refrigeration costs, projected to be at 23% of total cable capital costs 8 years after commercial cable introduction, needs to be reduced over 50% in order to gain the economic advantages offered through HTS technology.

Rotating machines, motors, and generators will benefit from any standardization of cryocooling designs, though it is likely that larger capacity generators will be marketed first, as larger size and footprint requirements have less stringent constraints to early HTS technology approaches. Moreover, new capacity additions and replacement of retiring rotating power machinery open this market segment to HTS business development initiatives.

The continued national and state commitment to deregulation of electric utilities can be materially contributive to early success with HTS, assuming the technologies are sufficiently developed to time their commercialization/market entry with the new competitive environment of open electric energy markets. For example, one major impact could be relief of congested transmission by the higher HTS cable load-carrying capability.

4. Needs/Goals and Technical Directions

Clearly, cost issues dominate the future success of HTS devices. Implicit in this too broad generalization is that technical improvements and, in some cases, breakthroughs are needed to achieve efficient cooling performance. The recently released “Cryogenic Assessment Report (59)” recommends that:

- Standardization of power devices and concomitant cryocoolers can result in lower costs through higher volume production and product reliability.
- Minimize cold section moving parts in cryocooler designs, e.g., Stirling pulse tube.
- Development of 1-2 kW cryocoolers (at 70-80K) able to operate at 30% of Carnot and cost $25/W.
- Increase end-user (utility and industrial managers) familiarity and comfort with cryogenic system operations, maintenance and safety issues.
- For HTS cables, conduct R&D to lower cryostat heat losses (reduce system heat load) while improving cryostat reliability (minimize vacuum degradation).

ENVIRONMENTAL BENEFITS

Environmental benefits from the installation of HTS technology accrue in two forms. First, the higher efficiency of electric generation, transmission, distribution, and utilization results in a lowered generated power requirement, in turn lowering greenhouse emissions to the atmosphere. Second, the reduction of potential environmental pollutants, such as transformer oil, SF6 insulating gas, and high-density oil in cable systems, and the reduction of materials required for electric power components provide additional environmental benefits.

Presently, over 6.23% of all electricity generated is lost through transmission and distribution losses. Superconductive T&D could reduce this loss by about one-half, potentially dropping electrical requirements by about 3.12%, saving a respective amount of fuel now spent in generation, and resulting in fewer greenhouse gases, less pollution, less resource extraction, etc. In 1995, total installed generation capacity, utility and nonutility, was 776,365 MW (61, 62). Of this amount, 54% was coal-fired generation (46). Of this 54%, 3.67% amounts to 15,386 MW. If this amount of coal-fired generation could be displaced through the installation of HTS T&D, it would preclude the emission of 131 million tons of CO2; 24,232 tons of NO_x, and 846,000 tons of SO_x annually (1995) based on today's coal plant technology. An equivalent, additional amount of reduction would occur when HTS-based electric motors and generators are fully implemented.

Superconductivity is clearly an energy efficiency technology, which could play a strong supportive role to renewable electric generation. For example, it could be a substantial part of climate change reduction through the use of distributed renewable generation, since superconductive cables would lower the losses associated with T&D from isolated power plants. Renewable technologies, inherently, must be utilized where the renewable resources exist; i.e., solar technologies work best where there is intense and consistent sun, and geothermal electric generation and direct use are best employed where high temperature geothermal resources exist close to the earth's surface. Reliable and predictable wind power requires a reliable and predictable wind, and, the higher the velocity, the more power can be generated, and this doesn't happen just anywhere.

The best renewable resources are not necessarily near centers of demand or population centers. Extensive wind generation is possible in broad areas of Montana, but the power demand is closer to Chicago. The solar resources of Arizona, New Mexico, and desert regions of the West could generate electricity for Los Angeles and Dallas, but the power must be transmitted and distributed over great distances to make this possible. Today, the costs, losses, and difficulty associated with generating power great distances from the ultimate user are a significant hindrance to broader adaptation of renewable energy options.

For many years, superconductivity was simply a research program whose promise was long term at best. Today, the technology has come to the point where the world's largest electrical cable producers and electrical equipment manufacturers are now deeply involved with their own funds. Years are still left before this technology will be widely available, cost effective, and in common use but when this happens, the substantial improvements in T&D efficiency this technology will bring will overcome these hindrances to wide renewables usage. HTS technology is strongly synergistic with energy efficiency and renewable technology projected benefits.

CONCLUSION

It is clear that HTS products and applications have a promising future. The only question is "when," and the foregoing analysis attempts to answer the "when" question based on the evidence, program plans, and insights available. Cost and performance trends are very promising. A leading HTS materials supplier has told the authors that the basic cost of materials, over the past ten years, has decreased by a factor of 1000. This supplier has also indicated that he can see another factor of five by which the materials costs are likely to decrease in the next few years.

A critical point regarding the capability of the product concepts to enter and capture the market has to do with product costs and the capability to lower present costs. Even if the high present prices are tied to fundamental materials costs, which are hard to lower, materials suppliers continue to be optimistic about further price decreases. If the high price is tied to manufacturing costs, then price reductions become inherently feasible, since, by design, increased production and the associated increase in automation will substantially lower total manufacturing costs. The authors have found no "show stoppers" in this process of continuing to improve the technology while lowering costs, so there is substantial reason to believe that the foregoing market penetration analysis is credible, and we can expect to see the benefits of HTS materials and products, commercially, in the near future.

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APPENDIX I:

FOUNDATIONS
for
SUPERCONDUCTIVITY
ANALYSIS

INTRODUCTION AND PURPOSE:

The accurate prediction of future events relies on consistent analysis using applicable methodology based on a series of facts and credible assumptions from which the calculations proceed. Numerous firms and organizations are now involved with performing a variety of Superconductivity analyses, and, often, these efforts begin with differing sets of facts and assumptions. Although differences in approach and methodology can lead to healthy and useful debate, differences in beginning assumptions brings the level of debate back to a point prior to the analysis, and this is less than helpful.

Over the past seven years, Bob Lawrence & Associates, Inc. has been working under contract to the Oak Ridge National Laboratory (ORNL) to track the projected markets for products envisioned to evolve based on superconducting technologies. Concurrent with this project has been an ongoing analysis of the eventual benefits that will result from commercialization of superconducting technologies. This effort has produced a wealth of knowledge continuously drawn upon for requested analyses. The information is based on over 80 references, utility surveys, ongoing tracking of trade publications, and continuing input from Superconductivity Partnership Initiative participants. In addition, the database of facts and assumptions has been thoroughly scrutinized by electric industry experts at the Oak Ridge National Laboratory.

Since the publication of the Products and Benefits 2000 report, Bob Lawrence & Associates has carried out additional analysis by looking at other market parameters of interest. For this analysis, further research was accomplished to develop an even greater array of facts and assumptions than was published in the Products and Benefits 2000 report.

The purpose of this Appendix is to assemble all of the Facts and Assumptions that our firm has developed to date and present them in a way which allows the most consistent analysis possible of this very important, evolving technology. We welcome all comments or questions regarding this material.

ELECTRIC INDUSTRY MARKET GROWTH:

In prior reports, BL&A has projected, for the next 20 years, an average annual growth in demand and generation of 2.5%, based on historical numbers. From 1986 to the present, electric generation has had average end-use increases of 2.5% per year. Inexplicably, during the mid and late 1990s, the Energy Information Administration (EIA) steadfastly predicted average future growth of 1.4% per year, 44% less than the historical average. At the present writing, EIA has now adopted a projection of 1.8% average increase, per year, through 2020, with a "high" case of 2.5%. Since 1995, Bob Lawrence & Associates, Inc. (BL&A) has been predicting annual growth of 2.5%, based on historical precedent and other factors. In projecting future electric growth, BL&A subscribes to the following rationale:

a) There is no immediate or readily apparent reason to believe that economic growth over the next 20 years will be a different average than the past 15 years (since 1986), once our economy is past the effects of 2001;

b) The effects of user efficiency increases vs. needed generation increases over the past 15 years have set a pattern which shouldn't differ greatly between now and 2020;

c) The economic growth prior to 2001 was largely based on electricity-using computers and manufactured items that incorporate electricity-using computers;

d) The pace of technology improvements in computer based and computer related technologies is such that a pattern of expansion of electricity consuming, computer integrated technologies is seen in more and more aspects of human life;

e) Electric demand will drive electric supply. Therefore, the demand average growth of 2.5% must also be taken as the projected generation growth.

f) The increased use of natural gas as the preferred fuel for new generation will result in lower electric energy prices through 2015 with a gradual rise following.

For these reasons, BL&A believes that it is realistic and intellectually correct to continue with the projection of an average 2.5% annual generation growth for the next 20 years. Table (X) is a projection of Electrical Industry Capability, Net Generation, and Total End Use from 2000 (hard data) through 2020, projecting 2.5% average growth from 2000 forward.

Table (X) Generation and End Use Projections
At 2.5% Average Growth per Year

Year	Generation Billion kWhr	End Use Billion kWhr	Avg Cost Cents/Kwhr (EIA Projection)	Required Capability (MKw)	
2000	3792	3607	6.3	818.5	(Actual)
2001	3887	3697	6.9	839.0	
2002	3984	3790	6.8	859.9	
2003	4084	3884	6.7	881.4	
2004	4186	3981	6.6	903.5	
2005	4290	4081	6.5	926.1	
2006	4398	4183	6.4	949.2	
2007	4507	4288	6.3	972.9	
2008	4620	4395	6.3	997.3	
2009	4736	4505	6.3	1022.2	
2010	4854	4617	6.3	1047.7	
2011	4975	4733	6.3	1073.9	
2012	5100	4851	6.3	1100.8	
2013	5227	4972	6.3	1128.3	
2014	5358	5097	6.3	1156.5	
2015	5492	5224	6.3	1185.4	
2016	5629	5355	6.4	1215.1	
2017	5770	5488	6.4	1245.4	
2018	5914	5626	6.5	1276.6	
2019	6062	5766	6.5	1308.5	
2020	6214	5910	6.6	1341.2	

Dates of Market Entry and 50% Capture:

Transformers and cable are projected for entry in 2005 followed by electric motors in 2008. The final market entry will be by generators, predicted for commercialization in 2009.

A key element in the analysis is the point at which the equipment will capture 50% of the potential market. The results predicted are found in Table 2 and are based upon adoption of HTS technology in keeping with other energy efficiency technology such as the high efficiency gas furnace.

Table 2: Year of 50% market penetration.

Equipment:	**Motors**	**Transformers**	**Generators**	**Underground cable**
This year sales: 50% of Market	2018	2015	2019	2013

<u>General Facts and Assumptions</u>:

Since the cost of HTS technology and the value of non-energy savings benefits are presently not well defined, this benefits assessment does not attempt to quantify these values but considers instead only the quantity and value of the energy saved. One way to look at this is to consider that the discounted values of these non-energy savings benefits are equal to the cost differential between HTS and conventional technology. In this way, energy savings becomes the surrogate and driving force for the market penetration. If non-energy savings benefits are (as many suggest) greater than the first cost differential, market penetration may be expected to proceed faster than projected in this report. Of course all market penetration models assume that production capacity can be established in the required time frame.

1. Assumption: The present EIA projection of average electric retail prices is adopted as correct. The EIA projects a slow drop in price until it reaches 6.3 cents in 2007, then flat until 2015, then rising from 2016 to 2020 where it reaches 6.6 cents. This is based on the 2.5% average end-use growth scenario.

2. Assumption: HTS-based transformers, cables, motors, generators, and fault current limiters will all enter the marketplace with first commercial items in the next 5-10 year period. This is the projected time period by virtually all authors of articles reviewed for this report. The question then becomes, *what is the relative shape of the S-curve adoption period of the technology; i.e.,* ***how fast does the technology penetrate***?

3. Fact: Total electricity delivered to ultimate customers is EIA stated net generation less 6.23% lost in the transmission and distribution process. While the T&D loss is assumed constant in this report, some recent indications support a larger growing value. This appears to be the result of inefficient power transfers in the deregulated utility environment.

4. Fact: In 2000, total sales of electricity to ultimate customers were 3607 billion kWh. Total sales revenue was $228 billion.

5. Fact: Nonutility generation capacity was 12.6% the size of utility generation capacity at the end of 1998. This amounted to 98,085 MW counting only the

total installed capacity of nonutility power producers with an installed capacity of 1 MW or more.

6. Fact: Total installed "capability" (slightly different from capacity) in 2000 was 818,500 MW.

7. Assumption: From 2000 through 2020, net generation and end use will average annual increases of 2.5% .

8. Fact and Assumption: From 1992 through 1998, annual increases in generating capacity averaged 0.5%. Clearly, capacity increases are not matching needed generation increases. Therefore, it is ***assumed*** that, added capacity will average 2.5% per year in the time period of introduction of HTS devices.

9. Assumption: On a 1-to-1 substitution basis, HTS devices will save ½ of the present energy losses in cables, electric motors, generators, and transformers. Comparing same cross sections of the engineered applications of HTS material to copper or aluminum materials indicates that in the HTS application the material can carry up to 100 times more current at virtually no resistance in the same cross section. However, HTS devices, of necessity, have only about 10% HTS material in the engineered cross section and require refrigeration (a parasitic loss). The calculated result generally falls into the range of 50% for savings of presently lost (wasted) energy.

10. Fact: All generated electricity goes through nominally 4 stages of transformers between the generator and the final point of use. For each 1 MVA of generating capacity, there are 3 to 4 MVA of transformer in place. For the purpose of analysis, 3 transformers is used as the assumption. When loading levels on the transformers are considered, about 50% of all transformer MVA is found in the transmission system, and 50% in the distribution system.

11. Assumption: One-half of all U.S. power transformer sales will be in the class of 30 MVA, 138-kV/13.8-kV transformer rating for the next two decades.

12. Fact: Power transformers are 99.3 to 99.7% efficient for the 30 MVA, 138-kV/13.8-kV class. However, they are purchased with excess capacity to meet maximum power and temperature limits. Therefore, they operate well below design level for the majority of the operating period and typical evaluation programs force the design to produce the maximum efficiency at or near the expected average loading point. Indeed the full load efficiency is generally 0.1-0.2% below maximum efficiency. Power transformers are responsible for 25% of all transmission/distribution losses, equal to $2 billion annually.

13. Assumption: HTS underground cable savings can reach 125,000 kWh per mile per year, or based on 6.89 cents per kWh, a monetary savings of $8612.50 per mile per year. This is equivalent to saving ½ the presently lost power in underground cables.

14. Fact: 64% of all electrical power passes through electric motors, with ½ of this passing through large motors.

15. Fact: Today's electric motor efficiency numbers are estimated to be 96% for General Electric's best to 92% for the average installed large motor. Reliance Electric estimates that today's "average practice" motor (100hp and up) is 95.9% efficient, compared to their estimate of 98.1% efficiency for an HTS motor equivalent. Therefore, it is assumed that any substitution of an HTS motor for a presently in-place motor would save 50% of presently wasted energy, accounting for the necessary cryogenic cooling inherent in the system.

16. Assumption: In a similar fashion, generator losses will be reduced by 50% when present systems are replaced by HTS technology systems.

17. Fact: Presently operating large electric motors (early HTS candidates) use 30% of all electricity generated in the U.S. This is the equivalent of $65.4 billion in retail sales of 1998 generated electricity delivered at the point of end use. According to a Reliance Electric study, the large industrial electric motor market is $300 million per year.

18. Fact: GE produces 10-20 generator replacement rotors per year and 120-150 generators per year in sizes 25-1650 MVA. GE assumes that HTS near-term potential is (worldwide) 100 units per year plus unit upgrades, and 30-40 rotors per year.

19. Assumption: The annual growth rate in the cable market for HTS cable will be 3.4% per year.

20. Assumption: A cable demonstration project of at least 3-5 years will be required to achieve market acceptance.

21. Assumption: HTS cable with life-cycle costs equal to conventional cable and with twice the ampacity would capture 56% of the underground transmission market 10 years after the first commercial sale.

22. Fact: In 1995, there were 3580 miles of underground transmission cable in the U.S. The market in that year for U.S. sales was 158 miles of which 18 miles were replacement sales and 140 miles were new installations.

23. Fact and Assumption: In any given year, 12% of the total population of all motors in the 5-500hp class fail. Of these, ½ are rewound and ½ are replaced. The replacement rate on large (>1000hp) motors is uncertain but, for the purpose of this analysis, the same failure/rewind/replacement rates are assumed since no better assumptions seem to be available.

Kiloamp-Meter Requirements by Product:

Our thanks goes out to the program managers within the Superconductivity Partnership Initiative (SPI) who donated their time and effort to provide us with the following information regarding required kilo-amp meters of superconducting wire per product described:

Electric Motors: To reach numbers for the coated conductor (tape) requirements for electric motors, David Driscoll of Rockwell Automation was contacted. Mr. Driscoll is the program manager for Rockwell's HTS motor development program. Examining present HTS motor designs, a 5000 horsepower motor will utilize 5000kA-meters of tape. Similarly, a 1000hp motor will utilize 1000kA-m of tape. Tape requirements scale relatively linearly with horsepower.

Transformers: Sam Mehta and Mike Walker at Waukesha Electric Systems report that a 100MVA transformer, under present design, calls for 10,000 kA-m of tape, a requirement linearly scalable within the power levels of interest.

Generators: HTS coated conductor tape requirements for generators are assumed to have the same kA-m per megawatt ratio as electric motors.

Cable: For the purpose of this study, both Southwire and Pirelli were contacted (R. L. Hughey and David Lindsey at Southwire, Nathan Kelley at Pirelli), and four cable geometries/specifications were examined. They were:

Southwire:
1680A, 3 phase cable (requires 12.6km of wire at Ic=30A per 100ft of cable)
3120A, 3 phase cable (requires 23.1km of wire at Ic=30A per 100 ft of cable)

Pirelli:
Pirelli warm dielectric (retrofit) cable at 2000A, 3 phase: 450kA-m per 100ft
Pirelli cold dielectric, coaxial cable at 2600A, 3 phase: 900kA-m per 100ft

Fault Current Limiters: Conversations with Eddie Leung, formerly of General Atomics, indicate that a 15kV, 45kA (asymmetric) FCL (rated 17kV, 45kA, or 765MVA) requires 1000 kA-m of tape (or wire) for each phase, or 3000 kA-m for each machine. This is virtually the same as the requirement for a 30MVA transformer.

Wire Pricing per Kiloamp-Meter:

There is a continuing conversation regarding the required market entry price of HTS wire in order to assure competitive product pricing. The projected, needed wire cost ranges, in various conversations and discussions, from $10 per KA-m up to $300 per KA-m.. In conversations with present cable and wire manufacturers, the comparable price of copper wire, today, is $23 per KA-m.

Conclusion:

As electric utility superconducting products edge closer and closer to market reality, it becomes more and more important that analysis be carried out consistently, with underlying data and assumptions, which are as accurate as possible. It is the intent of this Appendix to provide as much of that underlying data as possible from research and analyses, which have been carried out over the past six years. All comments and discussions regarding this information are welcomed, and updated data will be greatly appreciated.

APPENDIX II:

TABLES USED FOR ANALYSIS

Electric Generation and Use
Utilities and Nonutilities
1989 through 2000

Year	Net Generation Billion kWhrs	Percent Increase	Total End Use (BkWhr)	Percent Increase	Losses & Unaccounted	Losses (%)
1989	2972		2747		236	7.94
1990	3025	1.78	2817	2.55	210	6.94
1991	3071	1.52	2873	1.99	218	7.10
1992	3083	0.39	2885	0.42	224	7.27
1993	3197	3.70	2988	3.57	236	7.38
1994	3254	1.78	3075	2.91	223	6.85
1995	3358	3.20	3162	2.83	235	7.00
1996	3447	2.65	3250	2.78	237	6.88
1997	3494	1.36	3295	1.38	234	6.70
1998	3618	3.55	3424	3.92	220	6.08
1999	3706	2.43	3501	2.25	234	6.31
2000	3792	2.32	3607	3.03	221	5.83
Average Increase (%)		**2.24%**		**2.51%**		**6.23%avg** (4 Years)

Table "B". Revenue from Electric Utility Retail Sales of Electricity by Sector, 1991 through 2000 (Million Dollars) From EIA Electric Power Annual

Year	Residential	Commercial	Industrial	Other	All Sectors
1991	76,828	57,655	45,737	6,138	186,359
1992	76,848	58,343	46,993	6,296	188,480
1993	82,814	61,521	47,357	6,528	198,220
1994	84,552	63,396	48,069	6,689	202,706
1995	87,610	66,365	47,175	6,567	207,717
1996	90,501	67,827	47,385	6,741	212,455
1997	90,694	70,482	46,772	7,110	215,059
1998	93,164	71,769	46,549	6,864	218,346
1999	93,476	72,757	46,847	6,793	219,872
2000	98,172	75,249	47,818	7,074	228,313

Sources: Energy Information Administration, Form EIA-826, "Monthly Electric Utility Sales and Revenue Report with State Distributions," and

Form EIA-861, "Annual Electric Utility Report."

Table (X) Generation and End Use Projections
At 2.5% Average Growth per Year

Year	Generation Billion kWhr	End Use Billion kWhr	Avg Cost Cents/kWhr (EIA Projection)	Required Capability (MkW)	
2000	3792	3607	6.3	818.5	(Actual)
2001	3887	3697	6.9	839.0	
2002	3984	3790	6.8	859.9	
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2017	5770	5488	6.4	1245.4	
2018	5914	5626	6.5	1276.6	
2019	6062	5766	6.5	1308.5	
2020	6214	5910	6.6	1341.2	

APPENDIX III:

UTILITY SURVEY: OVERALL SUMMARY

UTILITY SURVEY: OVERALL SUMMARY

As part of the contract work statement, Bob Lawrence & Associates conducted a 10-question utility survey primarily during October and November 1997. The survey was faxed to each participating utility several days before our interview and used as a basis for discussion. The survey was a great help in our discussions, as it facilitated conversations and enabled a coordinated approach to all the participating utilities.

In all, 17 utilities representing all regions of the country took part in the survey. The nation's second-largest investor-owned utility (Southern California Edison) is represented, as is the nation's largest municipally owned utility (Los Angeles Department of Water and Power). A federally owned power marketing association is represented in the Western Area Power Administration, while almost all the regions of the North American Electric Reliability Council in the continental U.S. are covered. The fuels used by the participating utilities range from mostly coal (i.e., Public Service Company of Colorado) to mostly nuclear (Commonwealth Edison), and mostly hydropower (Western Area Power Administration). We believe that we achieved a fairly representative sampling of utilities through these 17 participants.

OVERALL IMPRESSIONS

Although all the participating engineers were aware of HTS in general, not all of them could summon up great enthusiasm for adopting the technology in their companies, due primarily to several issues which were raised frequently by the participants through the course of our discussions:

ISSUE: "HTS IS EXPENSIVE"

Regardless of the degree to which engineers supported HTS, most expressed concern over the perceived high cost of HTS as compared with conventional technologies, particularly in view of the increasing importance of initial capital costs in a competitive market. The following comment by Bob Whitford of Niagara Mohawk was typical of prevailing utility attitudes toward capital costs:

> "Life-cycle costs are the deciding factor at Niagara Mohawk right now, but this will definitely change with deregulation...right now, you're there for the customer no matter what. Under deregulation, costs are more important and initial costs will be especially important."

In much the same vein, Don Fagnan of PECO remarked that:

> "PECO's emphasis...is now on profitability. If a purchase doesn't represent a potential revenue gain now, then we won't do it, except to avoid a possible system catastrophe."

However, during our interview Fagnan was among the most proactive of the participants in bringing up the possibilities of HTS technologies, noting that even a 20% price premium for HTS equipment might be justified in certain crowded urban applications.

Despite the expressed concerns over the cost of HTS, some utilities saw great hope for the technology in the future. Several engineers ascribed the coming of deregulation as a potential boon for HTS, as utilities strive to differentiate their electrons in the competition for new customers. Bill Guyker of Allegheny Power pointed out, "conservatism and competition do not swing together." He said that a "new paradigm" is working in the industry and that competition is the "only way" to introduce new technologies.

Taking a slightly different tack, Rex Roehl of Commonwealth Edison said:

> "...deregulation will cause some utilities to become both more conservative and some to become more risk-taking. For example, recall that Sprint decided to install a fiber-optic network as a risk-taking move, although it hasn't knocked off AT&T yet."

Although some engineers felt that HTS could be justified to their companies' purchasing officers based on its merits, the bottom line remains a difficult barrier in the minds of some engineers. As Larry Conrad of Cinergy put it, "90 percent of [Cinergy]'s decisions are based on the bottom-line price." He said that there would be some interest in HTS transformers at his company, but added, "It's hard to change people's ways of doing things." Clearly, our conversations indicate that initial capital costs are becoming more and more important as utilities face an era of competition and much shorter depreciation periods, although the total owning, or life-cycle, costs will continue to play an important role in utility purchasing and decision making.

ISSUE: "UTILITIES ARE TOO CONSERVATIVE TO ADAPT READILY TO NEW TECHNOLOGIES"

One of the questions in our survey asked:

> "Utilities are traditionally considered to be very conservative in their adoption of new technologies. Do you think that the onset of competition will cause utilities to become even more conservative, or do you think that competition will help open the door to the introduction of newer technologies such as HTS?"

Many of the participants chuckled in agreement at the first sentence of this question. However, their views diverged on the second part of the question, with nearly equal numbers of participants feeling that utilities will become more aggressive and more conservative. The largest number of engineers felt that utilities will fall somewhere in the middle, becoming less conservative about adopting new technologies if the cost is right.

David Sweat of Tampa Electric wrote that competition "will open the door to newer technologies, but [utilities will] become even more conservative toward capital costs.

As Brian Egan of the Salt River Project said in his written reply:

> "We anticipate that deregulation will cause utilities to search out all avenues of technology that will enable them to better compete in the marketplace."

PECO's Don Fagnan echoed Egan's theme, saying that "if there's value added to a decision, then utilities will do it."

ISSUE: RESEARCH AND DEVELOPMENT FUNDING UNDER DEREGULATION

Several engineers noted that research and development budgets in their companies have been slashed or eliminated as companies approach deregulation. Jim Sandborne of PG&E and Paul Dalpiaz of PacifiCorp both mentioned recent cuts in R&D spending at their companies. Dalpiaz commented that "PacifiCorp's regulatory environment does not support a great deal of R&D."

Many of the engineers were grateful for the research efforts of the DOE and the Electric Power Research Institute (EPRI). The comments of Graham Siegel of Wisconsin Electric reflect the positive attitude shared by many engineers toward the DOE and EPRI work in this area:

> "I'm enthused and supportive of DOE's and EPRI's work on HTS and am cautiously optimistic."

However, Southern California Edison's Syed Ahmed, a self-described strong supporter of HTS technologies, remarked that the onset of competition will "starve investment monies."

Clearly, the prospect of industry deregulation and restructuring is having a dampening effect on utility investment patterns. With R&D budgets slashed, but without real competition having taken effect in most areas yet, it is difficult to assess how the new competitive environment will affect the pace of new technology introduction.

ISSUE: NEW TECHNOLOGY INTRODUCTION

It is "conventional wisdom" that utilities are traditionally very conservative in their adoption of new technologies. Our discussions with utility engineers confirmed that assessment, although as discussed above, the onset of competition may be changing the patterns of conservatism to a degree. Question 4 in our survey attempts to gauge the length of time that our respondents typically wait before introducing innovative new technologies into their system.

Question 4 asks:

"When a new technology is introduced into the commercial marketplace, how long would you generally like to see it prove itself in actual application before you make the decision to purchase it for your own utility?"

Most engineers, if giving a specific time period, said they prefer to wait three to five years before introducing new technologies. As Wisconsin Electric's Graham Siegel put it, utilities like to "charge ahead first to be second."

A number of respondents indicated that they are willing to try new technologies on a trial basis and participate in pilot programs. The Southern Company's Darrell Piatt noted that if utilities are engaged in sponsoring a new technology, then the adoption comes sooner. Pilot programs appear to remain the best way to introduce new technologies into utility usage. Even then, utilities seem to be concerned about reliability and the willingness of the manufacturer to stand behind the product.

ISSUE: PURCHASING APPROACHES: INITIAL CAPITAL COST OR LIFE-CYCLE COST?

Question 6 of our survey asked:

"Does your utility buy equipment with stronger emphasis on the initial capital costs or on life-cycle costs? Will your present purchasing approach change with deregulation?"

By a slight majority, respondents said that their companies put primary emphasis on life-cycle, or "total ownership" costs. Several asserted that they expected this emphasis on total ownership costs to continue under deregulation, while several others indicated that a shift toward initial capital costs was already beginning to take place due directly to the changing market. Bob Whitford of Niagara Mohawk said:

> "Life-cycle costs are the deciding factor at Niagara Mohawk right now, but this will definitely change under deregulation. Right now, you're there for the customer, no matter what. Under deregulation, costs are more important and initial costs will be especially important."

Larry Conrad of Cinergy probably provided the most apt summation of what appears likely to be an industry-wide trend as deregulation takes hold throughout the country:

> "Cinergy looks at the life-cycle costs with a bias toward low capital costs...our company is already operating under the assumption of deregulation."

Overall, our impressions from our conversations lead us to believe that utilities will continue to place importance on total life-cycle costs, but that utility purchasing managers will become increasingly sensitive to initial capital costs.

ISSUE: USING HTS AS A PR/MARKETING TOOL

Question 9 asked the utility participants:

"Do you foresee any marketing/PR advantage to using HTS (such as trumpeting the fact that your utility uses 'nonpolluting transformers and environmentally friendly transmission technologies')?"

By a slight margin, the participants appeared to agree that the use of HTS technologies could become part of their companies' marketing programs. Several engineers indicated that potential consumer desire for "green" power could provide an opportunity to market HTS in this manner. Wisconsin Electric's Graham Siegel said that "HTS technologies offer real value added and customers value our being innovative."

Generally, however, there appeared to be a distinct lack of enthusiasm for the possibility of using HTS as a marketing tool. The opinion of several participating engineers was that "price and performance" would be more important than marketing it to consumers. Cinergy's Larry Conrad said he didn't think that HTS would have "a heck of a lot of impact" on his company's customers, while Commonwealth Edison's Rex Roehl said that any good publicity resulting from HTS would be a by-product, rather than a driving force.

It is important to remember that these are primarily the opinions of technical personnel and not the utility marketing departments. Consumers have been shown to be sensitive to the environmental benefits of various products, from toilet paper to personal computers, and have paid more for products that claim to offer higher environmental quality than typical products. In the area of marketing environmentally clean electricity, or "green marketing," consumers in states around the country are willingly paying premium prices for power generated by clean renewable sources of energy such as wind, solar and geothermal. It is possible that once HTS technologies are commercialized, utilities will be able to market their environmental friendliness with measurable success.

ISSUE: OVERALL FEELINGS TOWARD HTS BY PARTICIPATING ENGINEERS

Question 7 asked the respondents to "characterize" their impressions of HTS technologies and how the technologies could benefit (or complicate) their companies' generating and transmission needs in the future.

Most participants extended positive evaluations to HTS; the most common qualifier was the cost and reliability issue. Jeff Fiske of Rochester Gas & Electric provided very short (written) answers to most of the questions. However, when asked for his overall impressions, he praised HTS, saying that it is a "terrific technology. When cost-effective, it will benefit."

The Los Angeles DWP's Mohammad Khajavi, in providing his overall evaluation, noted that one of the benefits of HTS is to carry a high load. However, we went on to say:

> [If HTS carries a high load,] You have the 'too many eggs in one basket' problem. Utilities should follow the 'N minus one' solution to avoid over-reliance on one single line or piece of equipment."

Khajavi's comments were echoed by several other participants, who do not wish to place an over-reliance on any one piece of equipment, no matter how reliable it is.

Interestingly, Bill Guyker of Allegheny Power expressed the hope that HTS would help lower total owning costs. As part of his overall impressions, he also stressed the need to educate personnel on this new technology as part of its adoption path.

Another positive overall evaluation of HTS was given by Larry Conrad of Cinergy, who said that:

> "Whether it's HTS or LTS, the 'H' tells me that it's more reliable, due to lower coolant costs. Benefits include power quality and reliability, and the energy storage potential, while there are few complications, except for the necessity of retraining personnel, which is no big deal."

Clearly, there are opportunities to advance utility acceptance of HTS, and emphasis on the technology's reliability and declining cost curve must rank near the top.

APPENDIX IV:

FOLLOW-UP SURVEY

FOLLOW-UP SURVEY

If high-temperature superconductive (HTS) power transformers became commercially available and were offered to your utility, how would you rank the following criteria in considering their purchase?

Competitive price with conventional transformers
very important <= 1 2 3 4 5 6 7 8 9 10 => least important

Reputation of manufacturer
very important <= 1 2 3 4 5 6 7 8 9 10 => least important

Manufacturer's warranty
very important <= 1 2 3 4 5 6 7 8 9 10 => least important

Post-purchase personnel training and education offered by manufacturer
very important <= 1 2 3 4 5 6 7 8 9 10 => least important

Track record of this technology
very important <= 1 2 3 4 5 6 7 8 9 10 => least important

Environmental considerations
very important <= 1 2 3 4 5 6 7 8 9 10 => least important

Smaller size and weight
very important <= 1 2 3 4 5 6 7 8 9 10 => least important

Advanced features (i.e., overload capability)
very important <= 1 2 3 4 5 6 7 8 9 10 => least important

Other:
very important <= 1 2 3 4 5 6 7 8 9 10 => least important

Future HTS transformers could possibly have dual capabilities: to limit "fault currents" as well as provide improved transformer performance. As you know, fault currents are large currents caused by "accidents" (lightning strikes for example) that can severely damage equipment before conventional circuit breakers react to give protection. Utility components protected by reliable fault current limiters could be lower cost since the expected maximum current would be significantly lower. The U.S. Department of Energy, in conjunction with its research partners, is developing fault current limiters (FCLs) that are fast-acting, passive devices (react without needing sensors to detect the fault), which could be combined into HTS transformers.

Would this dual capability make you more favorably inclined to purchase superconductive transformers? Yes No

Would you be willing to pay more than for conventional transformers? Yes No
If so, by what approximate percentage? %