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HIGH TEMPERATURE SUPERCONDUCTIVITY:

THE PRODUCTS AND THEIR BENEFITS

2000 Edition

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PREFACE

The first version of this report was completed in July of 1998 and further revised in January of 1999. It was published using available Department of Energy (DOE), Energy Information Administration (EIA) data and projections through 1996. Projections at that time were developed based on two scenarios: Case 1 was based on an electric growth projection 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. Case 2 was based on EIA conservative assumptions which led to an electric demand growth projection of 1.4% per year through 2020. The present document, and its included analysis, were developed by utilizing the data base developed for the first publication, and modifying it appropriately based on programmatic and market changes between 1996 and the present. The latest market data available is EIA information through December 1998. The programmatic data is from workshops and seminars during 1999, supplemented by recent interviews with project principal investigators.

There have been some significant developments in the past few years. First of all, electric growth has been following the projections of BL&A rather than those of EIA. Retail electric prices stayed well above EIA projections and demand growth was nearly double the EIA projection. Also of note, the transmission and distribution system appears to be getting dramatically less efficient (perhaps based on restructuring and long distance wheeling) instead of more efficient. The historical grid losses of 7.34% jumped to 10.13% in 1997 and 11.05% in 1998 (1).

The dates of projected market entry for this report remain the same as the original projections, largely due to the fact that the HTS product development programs remain essentially on the same schedule.

For the present analysis, Case 1 projections retained the 2.5% growth rate, but now include a declining electric price based on EIA projections. Case 2 base assumptions contain the same 1.4% growth rate, but a slower decline in electricity price and a 1998 demand starting point which is significantly higher than that assumed in the prior analysis. As a result, the Case 1 results fall below the projections of the last report, but the Case 2 projections fall significantly above the prior report. A complete list of facts and assumptions used for the analysis appears as Appendix I to this report.

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. 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 benefits projected from the commercialization of HTS systems (see References); however, few are available with quantitative predictions of market penetration and resultant benefits. 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 judgement, 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. These were developed based on an exhaustive review of References 1-53 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 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 under way 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 predicted to be fault current limiters, predicted for market entry in the 2003-2004 time period; however, the first market entry will probably happen in Japan or Europe before the U.S. Transformers and cable are projected for entry in 2005 followed by electric motors in 2006. The final market entry will be by generators, predicted for commercialization in 2011.

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 1: Year of 50% market penetration.

Equipment:	Motors	Transformers	Generators	Underground cable
This year sales: 50% of Market	2016	2015	2021	2013

Two cases were examined to predict benefits for market penetration of this equipment. The first case is based on electrical generation and equipment market growth averaging 2.5% per year through 2020. This number was chosen based on historic figures from 1990 - 1998 and the assumption that a strong economy will continue this kind of growth. Case 2 follows present EIA projections of 1.4% growth, with somewhat more conservative results. Benefits calculated are determined by the value of electricity saved that would otherwise be wasted. Operational benefits are not quantified.

For Case 1, annual benefits from all equipment types considered will be $503 million in 2010, $4.03 billion in 2015, and $14.7 billion in 2020. Cumulative benefits are $1.09 billion in 2010, $11.8 billion in 2015, and $61.2 billion in 2020. For Case 2 (the more conservative case), annual benefits become $437 million in 2010, $3.34 billion in 2015, and $11.7 billion in 2020. Cumulative benefits become $951 million in 2010, $9.97 billion in 2015, and $49.77 billion in 2020. For either case, the benefits of this technology are clearly substantial. All values are in constant 1998 dollars.

Environmental benefits from the installation of HTS technology accrue in two forms. First of all, the higher efficiency of electric generation, transmission, distribution, and utilization results in a lowered generated power requirement, resulting in lower greenhouse emissions to the atmosphere. Secondly, the highly efficient characteristics of HTS transmission and distribution (T&D) make it more economically viable to generate electricity from renewable resources, in remote locations, and utilize the resultant generation in distant population centers.

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 will be served by American industry 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, it is clear that the evolution of HTS equipment is a viable and critically important goal to pursue.

INTRODUCTION AND BACKGROUND

During the 20th Century, there have been many revolutionary technology advances, and when these advances have made their way into the marketplace, significant and substantial changes in our nation's productivity and standard of living have resulted. Some of the more prominent examples are solid state electronics, plastics technologies (including polyester), and aircraft materials which allow for high speed flight. More recently, computer memory technology has impacted our lives, with hard drives going from 10's of megabytes in the 1980's, to 10's of gigabytes today. In virtually every case, the basis of a "breakthrough" technology has been a fundamentally new understanding of the properties of a material or class of materials, when prepared in new and different ways. The purpose of this report is to examine, in as much as it is possible, the market emergence of yet 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. Few industrial or commercial applications have developed for these materials, however, (magnetic resonance imaging and kaolin clay separators being the exceptions) since they are characteristically very costly to make and are 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 which is the temperature of liquid nitrogen. Therefore, liquid helium costs about $5.00 per liter (2) whereas liquid nitrogen is only about 10 cents per liter. Thus, there are major cost and energy advantages of materials that are superconducting at 77 K as opposed to 4 K.

A dramatic change occurred in the potential application of superconducting materials when, in 1986, a new class of ceramic materials was discovered which showed superconducting properties at temperatures up to 34 K. 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 much less costly to produce. The materials themselves, however, remain costly to manufacture and very brittle in nature; however, 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 not an easy thing, 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. An example of this might be seen in 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 into products as individual components; then as small, discrete systems (radio signal receivers), and finally, as complete systems (solid state TV sets, computers), nearly totally replacing vacuum tube technology. 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 productivity of manufacturing, leading to wider availability and lower price, leading to further increased use. It is reasonable to assume that superconducting products will follow an analogous path.

There is yet another technological analogy which is interesting to examine when attempting to project the market entry of superconducting products; 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. It is 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. The standard gas furnace for home heating, at that time, was a 55% efficient furnace, noncondensing, 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 which showed that the reliability was acceptable, customer acceptance was good, and the price differential was justified 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 dominate the market, even when the market has a long history of being highly conservative. Superconducting products have the potential of following 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 precommercial 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" (3). 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 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." The Annual Energy Outlook '99 expects electricity demand to grow an average of 1.4% per year from 1997 through 2020 (4), with a new "high demand case" growth rate of 2.0% per year (average). Actual growth continues to exceed projections dramatically. EIA (4) blames this on not foreseeing the growth in home computers, fax machines, copiers, and security systems, all electric powered. The following table has the key data from the past few years:

Table 2: U.S. Electric Utility Sales to Ultimate Consumers and Associated Revenue by Sector: 1993 Through 1998 (Ref. 5).

Item	1993	1994	1995	1996	1997	1998
Sales (billion kilowatt-hours)						
Residential	995	1,008	1,042	1,082	1,076	1,128
Commercial	795	820	863	887	928	968
Industrial	977	1,008	1,013	1,030	1,032	1,040
Other 1/	94	98	95	98	103	104
U.S. Total	**2,861**	**2,934**	**3,013**	**3,097**	**3,139**	**3,240**
Avg. Revenue (cents per kWh)						
All Sectors:		6.91	6.89	6.86	6.85	6.74
Total Revenue ($ Billion):		**203**	**208**	**212**	**215**	**218**

Note: In the above table, net delivered Kwh increases an average 2.5% per year. This pattern extends back to 1990.

In this environment, transmission capacity has seen a 17% decrease from 1990-1999 (6). We cannot take for granted the ability of the present transmission system to continue reliable service (6).

Utilities are aging systems with aging equipment. 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; 60% of circuit breakers are more than 30 years old (6).

The grid is becoming less and less efficient. Electric generation in the U.S. (net) was 3494 billion kWh in 1997 and 3620 billion kWh in 1998 (1), an increase of 3.6%. Retail sales of electricity were 3140 billion kWh in 1997 and 3240 billion kWh in 1998. This is an increase of 2.6% (1). Therefore, generation and sales differed by 10.13% in 1997 and 11.05% in 1998. Of the 3240 billion kWh sold to ultimate consumers, 1664 billion kWh of this, or 51%, came from wholesale trade with other electric utilities (7). This may be the reason for the increase in percentage losses - i.e., transmission and distribution over longer distances.

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 (6). Urban and environmental requirements are driving towards a strong, robust grid, with the smallest possible environmental and land use footprint (6). 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.

363 GW of new generating capacity will be needed by 2020 to meet growing demand and replace retiring units (4). Assuming an average 300 MW per plant, this means 1210 new plants will be needed by 2020. This assumes the reference growth rate (1.4% per year). In the high EIA demand case (2.0% per year), an additional 113 GW more of new capacity will be needed than in the reference case (4). If the BL&A projections of 2.5% growth hold true, as has been the case, then the 363 GW requires an additional 285 GW for a total of 648 GW. Not surprisingly, over the next 20 years, an electric generation shortfall is seen (6).

In the AEO '99 forecast, it is assumed that electric generation demand will lag behind historic levels due to assumptions regarding efficiency improvements in end use technologies, demand side management programs, and population and economic growth. "Deviations from these assumptions could result in substantial changes in electricity demand." Examples given are electric vehicles entering the market, and/or lower electricity prices, due to increased competition, leading to increased consumption (4). The all-sector average electric price remained at 6.9 cents per kWh in both 1996 and 1997 (Ref. 4, Table A8). Between 1997 and 2020, however, the average price of electricity, in constant dollars, is projected to decline by 0.9% as a result of supplier competition (4).

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 (1) 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 nonutilities rose from 9 to 12%, primarily as a consequence of the sale of generating units by utilities to nonutility companies." During 1998, 593 MW of capability was added. Nonutilities presently plan 62 GW in capacity additions for 1999 thru 2003. Utilities plan 28 GW in additions (7), a factor of two less.

ULTIMATE BENEFITS

Dramatic cost and energy savings are projected when the candidate systems and products from superconducting technology are fully implemented, 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 presently lost electricity, lost in the T&D process through aluminum and copper-based infrastructure, alone. An additional $8 billion per year can be saved with the installation of superconducting transformers and electric motors (8). Yet another $2.24 billion or so can be saved by full implementation of HTS generators. This totals fully implemented benefits of $18.24 billion per year 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 kWh per mile, per year. At the 1998 average rate of 6.89 cents per kWh (4), this corresponds to retail level monetary savings of $8612.50 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 components that can survive industrial manufacturing and assembly"(2), and the need for high reliability, cost acceptable, cryogenic refrigeration.

Richard D. Blaugher 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 (9). 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 band of results. In order to carry out this analysis in the most credible fashion, the authors have endeavored to access the most credible, 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 "precommercial" 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 year, a prediction is made as to the timing of 10% market share of each product, 50% market share, and ultimate market share. These things will 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.

ANALYSIS

The analysis portion of this report is broken out 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 "precommercial" 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. Throughout the report, all values are expressed in constant 1998 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, training, manuals, parts availability, and all the beginnings of a logistics chain must be put into place.

Therefore, 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 rapidly increase to 50% of the market after an additional five years. This second assumption is based on present data showing the attractiveness, today, of high efficiency equipment in the electrical equipment markets. Final market share is analyzed separately for each potential product.

ELECTRIC MOTORS

THE MARKET

A promising situation 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 document restates the conclusion of an A.D. Little study that average annual hours of use for motors below 5 hp is in the range of 250 hours, while average use for motors over 50 hp 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 contains American Superconductor (wire manufacturer), Centerior Energy (utility end user), Air Products and Chemicals (industrial end user and cryogenics supplier) and Sandia National Laboratories. The motors being developed are in the "large motor" category (greater than 1000 hp) 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 these motors are well suited to utilize HTS technology. The worldwide market for HTS motors greater than 1000 hp is estimated to be $300M 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. 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 (9). It is indicated that the percentage remained at 64% through 1998 (6). As a percentage of total motor kWh, 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 50 hp (10, p. 3-11). "Above 126 horsepower" represents 33.3% of the total market, indicating why this design point was chosen by the Reliance team for their first demonstration motor.

"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, 5000 hp, high efficiency induction motor. This leads to reductions in friction and windage, core, stray load, and armature I^2R loss."(11)

The attractiveness of efficient motors over standard motors is increasing as may be seen from the following Table M-1 taken from Reference 14. The data is 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 list of 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 1998, total sales of electricity to ultimate customers was 3,240 billion kWh growing at 2.5% per year (Case 1) or, in the EIA case, 1.4% per year (Case 2). Therefore, the market to be addressed by HTS motors over 50 hp is a market using (.7 × .64 × 3240) 1452 billion kWh (1998) growing at 2.5% and 1.4% per year. Approximately 6% of the market inventory fails and is replaced every year, and another 6% is rewound.

TECHNOLOGY STATUS

As mentioned earlier in the report, the U.S. HTS electric motor team is headed by Reliance Electric with American Superconductor Corporation as the HTS coil supplier and manufacturer. Also on this team are Centerior Energy (a utility company) and Sandia National Laboratories. This team has designed, built, and successfully tested a four-pole, 1800-rpm synchronous motor using HTS windings operating at 27 K at a continuous 150-kW output. This output was some 25% above the motor design (14). It is safe to say that the promise of the HTS technology has been shown by this demonstration. This program has now been extended to "develop a pre-commercial prototype of a 3.7-MW (5000-hp) HTS motor" (14). An intermediate test, of a 1000-hp motor, is planned by 1999. 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 program successfully completed testing on a 200-hp prototype which exceeded design specifications by 60%. This singular success has led to the design of a 1000-hp motor to begin testing in February 2000. The final goal of this partnership program is to design and operate successfully, in an appropriate environment, a 5000-hp superconducting motor. Rotor prototypes for the 5000-hp motor are presently under test (15). The design point for operation of the 1000-hp motor is 27 K, using first generation BSCCO wire. The 5000-hp motor is expected to run at 33 K. Higher temperature operation would be desirable, but Rockwell feels that second generation wire (required for operation at 77 K) will not be available soon enough to be incorporated in the 5000-hp design (15).

The cost drivers for HTS motors are, as with virtually all HTS products, the refrigeration and wire costs. At this point in time, the 5000-hp 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. $2 to $4 per kA-m is really needed for broad market penetration (15). 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 (16).

MARKET PENETRATION

Demonstrations in an appropriate user environment are necessary for market development, and commercialization, to take place. The 1000-hp and 5000-hp motors are being developed for this purpose. Operation of the 5000-hp motor is scheduled for August of 2001 (15).

For the purposes of this study, then the multi-unit test is projected to begin in 2005, with 10% market penetration achieved by 2011. By 2016, 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 (Case 1) or 1.4% per year (Case 2).
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 2-½% added for a total of 8-½% 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 declines by 0.9% per year (Case 1 & 2 - Appendix II).

Therefore, benefits (kWh saved) are calculated as: $(3{,}240 \times 10^9$ kWh$) \times$ (Market Growth factor from 1998) × (.64) × (.7) × (% penetration) × (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. HTS electric motor penetration and benefits (Case 1).

Year	Market penetration (%)	This year sales: Energy saved (10^9 kWh)	Annual energy saved (10^9 kWh)	This year sales: Benefits (10^6 \$)	Annual benefits (10^6 \$)
2005	0	0	0	0	0
2006	1	.380	.380	24.09	24.09
2007	2	.797	1.177	50.05	74.14
2008	3	1.23	2.41	76.50	150.64
2009	5	2.10	4.51	129.36	280.00
2010	7	3.01	7.52	183.61	463.61
2011	10	4.40	11.92	265.76	729.37
2012	15	6.77	18.69	404.85	1,134
2013	22	10.18	28.87	602.66	1,737
2014	31	14.71	43.58	862.01	2,599
2015	40	19.45	63.03	1,128	3,727
2016	50	24.92	87.95	1,435	5,162
2017	60	30.65	118.60	1,753	6,915
2018	68	35.60	154.20	2,022	8,937
2019	75	40.25	194.45	2,270	11,207
2020	79	43.46	237.91	2,434	13,641

Case 1 shows that by 2010, HTS motors will save a cumulative 16.00 billion kWh equivalent to \$0.992 billion. By 2015, this becomes 182.09 billion kWh or \$10.919 billion. And finally, by the end of 2020, this technology will have saved a cumulative 975.20 billion kWh or \$56.781 billion.

Table M-3. HTS electric motor penetration and benefits (Case 2).

Year	Market penetration (%)	This year sales: Energy saved (10^9 kWh)	Annual energy saved (10^9 kWh)	This year sales: Benefits (10^6 \$)	Annual benefits (10^6 \$)
2005	0	0	0	0	0
2006	1	.353	.353	22.38	22.38
2007	2	.716	1.069	44.96	67.34
2008	3	1.09	2.159	67.80	135.14
2009	5	1.84	3.999	113.34	248.48
2010	7	2.62	6.619	159.82	408.3
2011	10	3.79	10.41	228.92	637.22
2012	15	5.76	16.17	344.45	981.67
2013	22	8.56	24.73	506.75	1,488
2014	31	12.24	36.97	717.26	2,206
2015	40	16.01	52.98	928.58	3,134
2016	50	20.29	73.27	1,169	4,303
2017	60	24.70	97.97	1,413	5,716
2018	68	28.38	126.35	1,612	7,328
2019	75	31.74	158.09	1,790	9,118
2020	79	33.91	192.00	1,899	11,017

Case 2 indicates that by 2010, HTS motors will save a cumulative 14.20 billion kWh equivalent to $0.882 billion. By 2015, this becomes 155.46 billion kWh or $9.328 billion. And finally, by the end of 2020, this technology will have saved a cumulative 803.14 billion kWh or $46.811 billion.

TRANSFORMERS

THE MARKET

The existing U.S. market for transformers in the 10- to 100-megavolt-ampere (MVA) class is $260 million per year (17). An additional market of $120 million exists for more powerful devices (17). The world market is at least 3-4 times larger and growing twice as fast.

From the list of 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 (18). For the purpose of this analysis, it is assumed that all generated electricity is transformed three times between the generator and the meter.

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 (19). 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 generally well below maximum efficiency. Nevertheless, power transformers are responsible for 25% of all transmission/distribution losses (19), or $2 billion annually.

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.” (19) 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 (20).

Transformer reliability is essential. Rochester Gas and Electric sees as key parameters for commercial acceptance: 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 (6).

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 accomplished. 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 as to 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, many of these safety procedures would be redundant with HTS transformers and we 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 if 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 percent"). 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 pursuing this technology in parallel. One team consists of Waukesha Electric (transformer manufacturer), Intermagnetics General Corporation (wire manufacturer), Rochester Gas and Electric (utility end user), Oak Ridge National Laboratory, and Rensselaer Polytechnic Institute. 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.

According to Mehta et al. (19), 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 connected the world's first operational HTS distribution transformer now powering the supply network of the city of Geneva.

A 1-MVA HTS transformer was tested by Waukesha in 1997. A 5/10-MVA HTS transformer is now being designed to power the Waukesha Electric Systems' plant. Component models are being tested. Installation is to occur in early 2001.

The ultimate goal of the Waukesha program is to develop and test a "pre-commercial" unit in the 30-MVA class. Multiple units would be delivered to "beta test" sites in the 2004-2005 time frame (20). A utility advisory committee is now being formed to identify 6-7 significant sites. The present sales force will be used for this new product and assembly and test will be incorporated into the present manufacturing facility (20). Once again, commercial success will be driven by the cost, and the main cost factors are the cost of the HTS materials and the refrigeration system. Presently available BSCCO wires, incorporated into the HTS coils, require cooling down to 25-30 K, using helium in a closed-loop circuit (cryocooler).

This team has conducted a series of reference designs concentrating mostly on a 30-MVA, 138-kV/13.8-kV transformer which, as noted earlier, is representative of a class expected to capture about half of all U.S. power transformer sales in the next two decades. For analysis purposes, this class and larger is expected to be handling in the range of 95% of all generated power. The 30-MVA "beta prototype" will be designed, built, and installed at a utility test site (21). "Crucial conductor and manufacturing process development will also occur during the 24-month effort." By the year 2001, this team intends to be marketing a commercial unit in this size range, so that 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 achieved, then consistent with our basic assumptions, 50% market share will be achieved by 2015.

ABB has previously designed, built, and operated an HTS transformer on a 630 kVA three-phase utility grid in Geneva, Switzerland. The present team intends 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 (22). A 100-MVA design will also be carried out. The later product will be cooled with liquid nitrogen, will be substantially lighter than conventional transformers, and will require no oil.

In Japan (23), 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 plans 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 will be accomplished with Kyushu Electric Power Company. This superconducting transformer will have a capacity of 500 kW, a primary-side voltage of 22 kV, and a secondary-side voltage of 6.9 kV. The coil will employ a wiring material made of bismuth-based oxide. Kyushu University verified the conductor characteristics in tests in which the occurrence of a short-circuit accident was simulated. In the tests, researchers ran an overcurrent that had about 10 times the amperage of the secondary-side rating (72.5 A) for 0.3 seconds in a mock-up coil that was 200 mm in diameter and 500 mm high, but there was no apparent degradation in the superconductor characteristics due to electromechanical force or the thermal expansion associated with the rise in temperature. 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 that are 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 (Case 1) or 1.4% growth (Case 2) plus replacements. The average transformer lifetime is estimated to be 30 years. Therefore, the average total transformer sales per year, including both new capacity and replacements, is estimated to be 5.8% of the total installed MVA (Case 1) or 4.7% (Case 2). From the foregoing discussion, total transformer installed capacity is approximately 3 times total generation capacity, or 784,777 MW (1998) multiplied by 3 equals 2,354,331 MVA (1998). The target market to be addressed by HTS equipment, then, is 50% of this amount multiplied by the annual sales rate (5.8% or 4.7%) equaling 68,276 MVA per year (Case 1) or 55,327 MVA per year (Case 2) based on 1998 generation. Consistent with the estimates of Mehta et al. (19), this is the equivalent of approximately 2278, 30-MVA transformers (Case 1) or 1844, 30-MVA transformers (Case 2). This target market, then, grows from 1998 in accordance with the growth rates assumed for Case 1 and Case 2 as does the total market.

As mentioned earlier, 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 7.34% of total generation (8,13), even though present system changes are leading to much higher losses (1). HTS transformers will save 50% of the presently wasted electricity in standard transformers. Therefore, the savings for each 1% of total market (2× initial HTS target market) penetration will be:

(One percent) × (total annual generation) × (7.34%) × (25%) × (50%) × (annual sales % of installed transformer capacity).

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

Table T-1. HTS transformer market penetration and benefits: Case 1.
[Generation/capacity growth rate $(1.025)^n$, total transformer market 5.8% of installed]

Year	% HTS penetration of total market	This year savings (10^9 kWh)	Annual savings (10^9 kWh)	Annual savings (10^6 $)	This year HTS sales (MVA)
2004	0	0	0	0	0
2005	1	.020	.020	1.28	1,623
2006	2	.042	.062	3.93	3,329
2007	3	.064	.126	7.91	5,118
2008	5	.110	.236	14.68	8,743
2009	7	.158	.394	24.27	12,548
2010	10	.232	.626	38.19	18,378
2011	15	.357	.983	59.37	28,247
2012	22	.536	1.52	90.90	42,456
2013	31	.775	2.29	135.57	61,352
2014	40	1.025	3.32	194.55	81,137
2015	50	1.313	4.63	271.32	103,954
2016	59	1.588	6.22	358.27	125,732
2017	66	1.820	8.04	459.89	144,168
2018	71	2.007	10.05	570.84	158,969
2019	74	2.144	12.19	687.52	169,828
2020	76	2.257	14.45	809.20	178,774

Therefore, by 2010, a total accumulated benefit of $90.26 million should occur from the commercialization of HTS transformers according to present projections. By 2015, this grows to $842 million, and by 2020, it is $3.728 billion.

Table T-2. HTS transformer market penetration and benefits: Case 2.
[Generation/capacity growth rate $(1.014)^n$, total transformer market 4.7% of installed]

Year	% HTS penetration of total market	This year savings (10^9 kWh)	Annual savings (10^9 kWh)	Annual savings (10^6 \$)	This year HTS sales (MVA)
2004	0	0	0	0	0
2005	1	.016	.016	1.02	1220
2006	2	.032	.048	3.04	2472
2007	3	.047	.095	5.97	3761
2008	5	.080	.175	10.89	6356
2009	7	.114	.289	17.80	9027
2010	10	.165	.454	27.69	13,070
2011	15	.251	.705	42.58	19,885
2012	22	.374	1.079	64.52	29,572
2013	31	.533	1.612	95.43	43,607
2014	40	.698	2.310	135.37	55,294
2015	50	.884	3.194	185.25	70,637
2016	59	1.058	4.252	244.92	83,812
2017	66	1.201	5.453	311.91	95,123
2018	71	1.309	6.762	384.08	103,724
2019	74	1.384	8.146	459.43	109,641
2020	76	1.442	9.588	536.93	114,180

In Case 2, by 2010, a total accumulated benefit of $66.41 million should occur from the commercialization of HTS transformers according to present projections. By 2015, this grows to $589.6 million and, by 2020, it is $2.527 billion.

GENERATORS

THE MARKET

The market for generators encompasses many shapes and sizes, from the small, portable equipment sized in the range of 1 kW, up to the large, stationary sized equipment used in base load nuclear plants sized 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 which are taking place, and a higher percentage of nonutility generation, the overall market is the total growing electric generation industry which was 784,777 MW (7) in 1998. From the list of facts and assumptions (Appendix I), utility and nonutility power generated in that year was 3,240 billion kWh at a value of $218 billion. Again, this market is assumed to grow at the rate of 2.5% per year for Case 1 and 1.4% per year for Case 2.

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 that 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 (24). The GE rotor assumption obviously takes into account the efficiency advantage of an HTS rotor being such that early replacement will be seen as 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 (25), 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 was a wide range 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.” In another report by Blaugher (26), it is stated that: “At first sight, the expected 1 percent or so increase in efficiency for the SC machine should cut a utilities’ annual fuel costs so much over the customer 40-year lifetime 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, as well, for the HTS equipment to be attractive.

TECHNOLOGY STATUS

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

Japan has 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”(27):

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.

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.”

Verification testing is being performed on the three different rotors having different specifications but with a common stator. These tests achieved numerous results, including the world's highest output (79 MW), and the world's longest continuous operation (1,500 hours) for a superconducting generator. These results indicate that prospects are good for the establishment of design and manufacturing technology for a 200,000-kW pilot generator.

The superconductive field winding is cooled using liquid helium, and is thermally shielded from the normal temperature parts by a vacuum insulation tank. To shield it from the ac magnetic field generated by the armature winding, a damper, similar to the ones used in generators currently in operation, is used outside the vacuum insulation tank.

Verification testing was aimed at determining the basic performance characteristics of a superconducting generator, verifying the long-term operation reliability and its cooling system, and the robustness required at system malfunction. It was also aimed at establishing design and manufacturing technologies for a 200,000-kW class pilot generator.

Based on the demonstrated efficiency of the model generator, it was estimated that the efficiency of a 200,000-kW class generator would be 99.10 percent. This value indicates an initial improvement in efficiency over conventional generators of roughly 0.6 percent for the superconducting generator itself, but 0.5 percent if operation of the cooling system is taken into consideration.

To simulate the most serious accident that can occur in a real electric power system, a three-phase short-circuit at a terminal very near the high-voltage side of a main transformer, a sudden three-phase short-circuit test was performed, during which electromagnetic torque of 4.06 pu (or 1.2 times that expected in an actual accident) was applied. When the sudden short-circuit occurred, the rotor was robust, exhibiting no sudden changes in shaft play, no abnormal increase of heat penetration, and no quenching. The robustness of the various parts of the stator -- coil, teeth, wedge -- were also verified by inspecting the stator following post-test removal of the rotor.

To simulate an unbalanced malfunction in a system, a large reverse phase test, was conducted. The cold damper remained well below the temperature limit, and quenching did not occur in the field winding at this time, thus verifying that the superconducting generator can withstand greater reverse current than conventional generators.

In a long-term reliability test, the model generator was run under continuous load for 814 consecutive hours, and if daily start-stop (DSS) tests are included, it achieved a continuous operation time of 1,500 hours.

The model generator exhibited stable, quenchless operating characteristics during continuous load testing, and at DSS operation. The test results described below also verified the stability and outstanding performance of the field winding relative to transient current fluctuations.

The electrical and mechanical strength of the slotted armature winding was proven through long-term reliability testing, and severe tests, which simulated system accidents. In all of the tests, the stator components remained thermally stable, and the strength and robustness of each component was verified via post-verification testing inspections.

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 goes on to point 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."

Clearly, the generator efforts in both the U.S. and Japan are well 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 five years behind HTS electric motor market penetration. Based on the foregoing data, this would appear to be a reasonable assumption. Therefore, the multi-unit test of generator technology is expected to begin in 2010, with 10% market penetration by 2016, followed by 50% of the market by 2021. This would appear to be consistent with the potential as described by GE and the description of the Japanese efforts.

In the limit (1998 values), fully installed HTS generators (utility and nonutility) would save \$2.44 billion per year (1% of total generation) based on numbers for 1998. The annual sales market, from our list of assumptions, is assumed to be 2.5% growth + 2% replacement (50-year life) for Case 1, or 4.5% of total electric industry capacity annually. This equates to 4.5% × 784,777 MW or 35,315 MW annually based on 1998 numbers. In Case 2, the growth is 1.4%, so the market becomes 3.4% of utility capacity annually. In Case 2, this equates to 26,682 MW (1998). Per sales year, implemented, retail value, electric savings become:

Case 1: (4.5%) × (\$2.44B) × ($[1.025]^n$) × (percent market penetration) × ($[0.991]^n$)
Case 2: (3.4%) × (\$2.44B) × ($[1.014]^n$) × (percent market penetration) × ($[0.991]^n$)

In case 2, the factor $(0.991)^n$ must be applied, as EIA estimates a 0.9% per year average decline in electric prices from the present through 2020.

Therefore, the market penetration expected and associated benefits for Case 1 and Case 2 are expressed in the following tables:

Table G-1. HTS generators:
Market penetration and benefits (Case 1).

Year	Market penetration (%)	This sales year benefits (% of ultimate)	This year sales benefits (10^6 $/yr)	Cumulative annual benefits (10^6 $/yr)
2010	0	0	0	0
2011	1	.045	1.35	1.35
2012	2	.090	2.73	4.08
2013	3	.135	4.16	8.24
2014	5	.225	7.05	15.29
2015	7	.315	10.04	25.33
2016	10	.450	14.56	39.89
2017	15	.675	22.17	62.06
2018	22	.990	33.06	95.12
2019	31	1.40	47.46	142.58
2020	40	1.80	62.02	204.60
2021	50	2.25	78.68	283.28

Although the benefits from generators are less than from motors or transformers, they are clearly significant accumulating to $882 million by 2021 in Case 1.

Table G-2. HTS generators:
Market penetration and benefits (Case 2).

Year	Market penetration (%)	This sales year benefits (% of ultimate)	This year sales benefits (10^6 $/yr)	Cumulative annual benefits (10^6 $/yr)
2010	0	0	0	0
2011	1	.034	0.88	0.88
2012	2	.068	1.78	2.66
2013	3	.102	2.68	5.34
2014	5	.170	4.48	9.82
2015	7	.238	6.31	16.14
2016	10	.340	9.05	25.19
2017	15	.510	13.64	38.83
2018	22	.748	20.13	58.96
2019	31	1.054	28.48	87.44
2020	40	1.360	36.95	124.39
2021	50	1.700	46.38	170.77

In Case 2, the benefits from generators are considerably less than in Case 1, but they are still significant, accumulating to $540 million by 2021.

UNDERGROUND POWER CABLES

THE MARKET

The market for underground power cables is relatively less complex than that for other potential HTS products which have previously been described. From the Appendix I list of facts and assumptions and their associated published studies, we know the total amount of installed, underground cable in the U.S. and much about the potential 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 (28). The annual growth rate in the cable market for HTS cable will be 3.4% per year (29). A cable demonstration project of at least 4 years will be required (29). 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 (29). 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 $8612.5 per mile per year. This is equivalent to saving ½ the presently lost power in underground cables (24).

Current estimates are that approximately 2200 miles of existing underground cable are at 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 needed right-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 (30).

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 (31). Some key early market examples are France (225 KV), Detroit (24 KV), and London (11 KV). The cost trade-off is seen as the additional cost of HTS cable vs the 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 4 years, in multiple units and in multiple utilities. At that point in time, commercial introduction could begin, following the path previously described.

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, Plastronic, Inc. (subsidiary of EURUS Technologies, Inc.), and Intermagnetics General Corporation (HTS tape development), Georgia Transmission (electrical systems design), Southern Company, and Southern California Edison (utility users). The second team is led by the Electric Power

Research Institute and consists of Pirelli Cables and Systems (systems manufacturer), American Superconductor (wire manufacturer), Lotopro (refrigeration systems), Detroit Edison (host utility), and Los Alamos National Laboratory. Additionally, in Europe, a cable commercialization group has formed lead 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 which require high amperage and only medium to high voltage, which are the optimum characteristics for HTS cables (31).

For Pirelli, early implementation/commercialization of HTS cables is seen in the 2003-2005 time period. Pirelli has successfully constructed and tested a 50-m underground transmission cable containing more than six kilometers of lead-stabilized BSCCO tape (30). A 100-m cable is expected to be installed and operational in Detroit in 2001. This will provide an opportunity for U.S. utilities to see, first hand, what the technology is capable of and to experience the operational and maintenance requirements (31).

Pirelli has designed and commissioned a dedicated HTS cable manufacturing line (33). 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 (31).

Pirelli is reported to have the most aggressive HTS cable demonstration program in the world, with demonstrations in Europe, Japan, and the U.S. The Detroit demonstration, now in its initial stages, will consist of three single-core, HTS cables, each 400-ft long and carrying 2400 A of alternating current at 24 kV, and a total of 100 MW of power. Superconductor Week (33) reports that Pirelli is developing advanced coaxial HTS cable systems in France, Germany, and Italy. "HTS cable commercialization (is) expected to follow current demonstrations."(33)

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 (34). In Germany, Siemens is working on "the first serially produced superconducting cable for 110 kilovolt service (to be ready) in late 1998." (35) The cable will be 50-m long.

The Southwire effort to get to commercialization consists of three phases (36). Phase I consisted of the design, manufacture, and test of four laboratory-scale cables: two 500-A cables and two 2000-A cables. Phase II, now under way, began in 1997 and is expected to require three years to complete. This phase contains three major components: 1) a more robust, shielded cable design that is suitable for service outside the laboratory; 2) the development of production machinery necessary to manufacture a 30-m length of the cable; and 3) the cable and its supporting cryogenic refrigeration system are to be installed under "real world" conditions, providing power to the Southwire Headquarters building and two cable production plants. The power this cable will carry will be the equivalent of that needed to supply the demand for a city of 16,000 people.

Southwire is coming to the end of a three-year project which will finish by testing three 30-m cables. Questions regarding terminations and refrigeration are to be addressed. This testing and evaluation will take place during 2000. Concurrently, Southwire has a dedicated HTS cable manufacturing facility in operation and the sales force is being readied for potential commercial sales (37). Southwire has built a special superconducting cable manufacturing facility in a clean room environment. A cable wrapping or stranding machine has been acquired and modified for winding superconducting cables (16). As need for transmission and distribution increases in a U.S. atmosphere of urban constraints and enhanced environmental awareness, a technology which can carry great quantities of electric power in confined, underground spaces will become more and more desirable. The Southwire team is pursuing a "cold dielectric" concept which, they believe, will lead to lower electromagnetic field losses and an overall, more efficient design. Liquid nitrogen is used to cool the cable (38). During 2000, an additional critical item to commercialization, HTS cable splicing, will be addressed jointly by Southwire and ORNL (16).

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 (37).

Tokyo Electric Power Company (TEPCO) and Sumitomo Electric announced 5 October (39) the joint development of a prototype, compact, HTS cable system 100 m in length that is ready for conduction tests. The prototype, which is nearing practical application, was developed using liquid nitrogen as the coolant. The conduction tests will begin in June of 2000 and should last for one year. The tests will be implemented at the Yokosuka Laboratory of the Central Research Institute of the Electric Power Industry (CRIEPI). The costs for the development are estimated at 1.8 billion yen and will be shared equally between the two companies.

Because the superconducting cable size is compact, the needed conduits for underground transmission lines are 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.

The conduction tests will focus on the verification of several areas. These areas include verification of system performance, analysis of technical problems that may arise when the cable is placed in a conduit with an inner diameter of 150 mm and verification of effects that refrigeration will have on the conductor.

If this type of cable becomes commercial practice, power transmission ten times that of what is now possible (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

Phase II of the DOE/SPI project will be completed during 2000, leading to the 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 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:

> Case 1: (% Market Penetration) × (158 miles) × ($[1.025]^n$) where "n" is the number of years past 1995. Dollar savings will be ($8,613) × (total miles) × ($[0.991]^n$) where "n" is here the number of years past 1997. The reason for this is that the average price per kWh in 1997 was 6.89 cents, the same as in 1995, but the cost seems to be declining from 1997 in line with the EIA assumptions (4).
>
> Case 2: (% Market Penetration) × (158 miles) × ($[1.014]^n$), and dollar savings will be ($8,613) × (total miles) × ($[0.991]^n$). Again, Case 2 (the EIA case) assumes a price of electricity decline averaging 0.9% per year through 2020.

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 customer's 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.

A more detailed and extensive analysis, resulting in much of the basic information for this portion of the study, was carried out by Forbes (29).

Table C-1. Underground power cables:
Market penetration and benefits (Case 1).

Year	% Market	Miles sold this year	Total miles installed	Total annual savings (10^6 $)
2004	0	0	0	0
2005	3.4	6.87	6.87	.054
2006	6.7	13.89	20.76	.165
2007	10.0	21.25	42.01	.331
2008	15.0	32.68	74.69	.582
2009	21.0	46.88	121.57	.939
2010	27.0	61.77	183.34	1.40
2011	33.0	77.43	260.77	1.98
2012	40.0	96.19	356.96	2.68
2013	48.0	118.31	475.27	3.54
2014	56.0	141.47	616.75	4.56
2015	63.0	163.15	779.90	5.71
2016	69.0	183.15	963.05	6.98
2017	74.0	201.34	1,164	8.37
2018	77.0	214.73	1,379	9.82
2019	79.0	225.80	1,605	11.33
2020	80.0	234.35	1,839	12.86

For Case 1, total accumulated savings through the year 2020 will be $71.3 million.

Table C-2. Underground power cables:
Market penetration and benefits (Case 2).

Year	% Market	Miles sold this year	Total miles installed	Total annual savings (10^6 $)
2004	0	0	0	0
2005	3.4	6.09	6.09	.049
2006	6.7	12.33	18.42	.145
2007	10.0	18.68	37.10	.289
2008	15.0	28.39	65.49	.506
2009	21.0	40.31	105.8	.809
2010	27.0	52.56	158.36	1.200
2011	33.0	65.12	223.48	1.679
2012	40.0	80.07	303.55	2.261
2013	48.0	97.38	400.93	2.956
2014	56.0	115.2	516.13	3.778
2015	63.0	131.49	647.62	4.692
2016	69.0	145.98	793.6	5.698
2017	74.0	158.78	952.38	6.777
2018	77.0	167.53	1120	7.897
2019	79.0	174.25	1294	9.043
2020	80.0	178.98	1473	10.20

For Case 2, total accumulated savings through the year 2020 will be $57.98 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), General Atomics (USA), Rolls-Royce and Merck (United Kingdom), and Siemens (Germany) (6).

The SPI fault current limiter team consists of General Atomics (systems developer and integrator), Southern California Edison (utility end user), Intermagnetics General Corporation (wire manufacturer), and Los Alamos National Laboratory.

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 as high as 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 (40).

The desire for HTS FCL products is substantially greater in Europe than in the U.S. (6).

FCLs represent a new class of electrical equipment that is 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 (41), 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.

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 (41).

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 withstandable 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."

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."

Taylor Moore (42) supports Leung's assertions. "Superconducting fault current limiters could afford utility equipment greater protection against large momentary power spikes caused by short circuits or lightening. 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."

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 which is 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. The 15-kV device now being tested will be able to operate at 20 kV. Operating temperature will be 40 K (21). It is planned to be installed at the Chino Substation in California and operated over several months to demonstrate capability for use by electric utilities (16).

At this point in time, the cost of these systems is still "prohibitive" (43) with 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 present cost is $500/kA-m, while 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 (43). It is felt that 77 K operation (liquid nitrogen temperature), using second generation wires or tapes, will be key to commercial success (43).

Utility acceptance will take considerable time and, therefore, demonstrations of the capabilities of this type of new equipment will be essential to marketplace success. In France, a team addressing this technology is led by GEC-Alsthom/Electricité de France; in Canada, a team consists of Siemens and Hydro-Quebec; and in Japan, the team consists of Toshiba and Tokyo Electric. In 1996, the Lockheed Martin team tested a 2.4-kV, 2.2-kA FCL on Southern California Edison's utility grid in San Diego (42). Based on the results of that test, a Phase II effort is now under way to build a precommercial unit rated at 15-kV, 20-kA rms symmetrical. This precommercial unit is expected to meet the market needs of being able to withstand multiple faults within a period of 15 s, as well as the other market needs previously mentioned.

MARKET PENETRATION

The present status of the equipment is the completion of construction and test of "precommercial" items. The completion of this single item testing is expected to occur in 1999, followed by multiple-unit testing in 2000-2001. In this scenario and being consistent with our prior market entry assumptions, 10% market share should be achieved by 2006, and 50% share would be achieved in 2011.

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. It has been suggested by some authors and some HTS experts 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.

The results of the analysis have been accumulated, for all products, in the following tables for Cases 1 and 2. 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.

A compilation of benefits can be found in the following tables.

Totals Table - Case 1, based on 2.5% annual growth in capacity and generation. Annual benefits in ($ × 10^6).

Year	Motors	Transformers	Generators	Cable	Total
2004	0	0	0	0	0
2005	0	1.28	0	.054	1.33
2006	24.09	3.93	0	.165	28.19
2007	74.14	7.91	0	.331	82.38
2008	150.64	14.68	0	.582	165.90
2009	280.00	24.27	0	.939	305.21
2010	463.61	38.19	0	1.40	503.20
2011	729.37	59.37	1.35	1.98	792.07
2012	1,134	90.90	4.08	2.68	1,232
2013	1,737	135.57	8.24	3.54	1,884
2014	2,599	194.55	15.29	4.56	2,813
2015	3,727	271.32	25.33	5.71	4,029
2016	5,162	358.27	39.89	6.98	5,567
2017	6,915	459.89	62.06	8.37	7,445
2018	8,937	570.84	95.12	9.82	9,613
2019	11,207	687.52	142.58	11.33	12,048
2020	13,641	809.2	204.60	12.86	14,668

In Case 1, by the end of 2010, benefits are projected to accrue totaling $1.086 billion. By the end of 2015, total accrued benefits become $11.8 billion and, by 2020, the accrued benefit is $61.2 billion. For this Case 1 analysis, substantial national benefits can accrue from this technology, expanding greatly into the 21st century.

Totals Table - Case 2, based on 1.4% annual growth in capacity and generation. Annual benefits in ($ × 10^6).

Year	Motors	Transformers	Generators	Cable	Total
2004	0	0	0	0	0
2005	0	1.02	0	.049	1.07
2006	22.38	3.04	0	.145	25.57
2007	67.34	5.97	0	.289	73.60
2008	135.14	10.89	0	.506	146.54
2009	248.48	17.80	0	.809	267.09
2010	408.30	27.69	0	1.200	437.19
2011	637.22	42.58	0.88	1.679	682.36
2012	981.67	64.52	2.66	2.261	1,051
2013	1,488	95.43	5.34	2.956	1,591
2014	2,206	135.37	9.82	3.778	2,355
2015	3,134	185.25	16.14	4.692	3,340
2016	4,303	244.92	25.19	5.698	4,579
2017	5,716	311.91	38.83	6.777	6,074
2018	7,328	384.08	58.96	7.897	7,779
2019	9,118	459.43	87.44	9.043	9,674
2020	11,017	536.93	124.39	10.20	11,689

In Case 2 (using EIA projections), by the end of 2010, benefits are projected to accrue totaling $951 million. By the end of 2015, total accrued benefits become $9.97 billion and, by 2020, the accrued benefit is $49.77 billion. Clearly, even this highly conservative analysis shows that substantial national benefits can accrue from this technology, expanding greatly into the 21st century.

TECHNOLOGY CONSTRAINTS TO COMMERCIALIZATION

The two main constraints to commercialization are consistently expressed by systems developers as the cost of the superconducting material itself, and the cost and complexity of the required refrigeration systems. It is hoped that second generation wire now under development may help to alleviate both of these technology constraints, as second generation wire is thought to have considerable cost advantages in terms of dollars per kA-meter, and it will also require temperatures of liquid nitrogen as opposed to 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

American Superconductor is now claiming that with their BSCCO-2223 wire technology (first-generation technology), they are achieving an "average strand engineering critical current density (J_e) of 14 kA/cm^2 over a 17-km manufacturing run" (44). ASC also claims a process of making the wires more robust by adding a 35-µm layer of stainless steel to both sides of a tape. This reduces J_e by 33% but allows the tapes to withstand nearly 400 Mpa of tensile stress and 0.5% tensile strain at 77 K. In 25-km quantities, ASC is now advertising a price of $300 per kA-meter (77 K, self-field). At a manufacturing rate of 2000 km per year, ASC feels that this cost would drop to $50/kA-m. By operating these same wires at 27 K, the price would drop to $25/kA-m (according to ASC) due to the increase in performance at the lower temperature. ASC Chief Technical Officer, Alex Malozemoff, is quoted as saying: "There are a range of applications where $50/kA-m is adequate for commercial systems. However, for the broader application range we need to push BSCCO technology further or look forward to the next generation wire technology." (44)

The second-generation wire being developed under the DOE program has the goals of manufacturability in lengths exceeding 100 m and current density capability of 500 A per square millimeter. (45)

In Japan, wire development moves forward aggressively. Chubu Power announced 13 October (46) the development of new wire material production technology for a superconducting cable. The new technology was developed jointly with Fujikura. The new production technology can form high performance yttrium-based superconducting wire material at a speed several times faster than former methods where generally, one hour is required to form each meter of wire. Using this new technology, the group is aiming at the development of the world's first wire material several kilometers in length.

Bismuth and yttrium are the chosen high temperature superconducting materials that use liquid nitrogen refrigeration. Yttrium is suitable for use in cable material because it enables large current capabilities and has stable performance. However, production requires a great deal of time because a chemical vapor deposition (CVD) method is used. This method involves changing the material to a gaseous state on an atomic level and then causing crystallization to occur on the surface of the base material. To date, the material has not been used in cables because of the great deal of time it would take to produce those lengths.

Both companies increased the feed rate of the base material while using the CVD method and introduced a multi-stage synthesis method in which the surface on which crystallization occurs is increased and the material is then separated into several layers to form crystals. The group also established technology for synthesis between layers on an atomic level. In tests, the production of the wire material occurred at three meters per hour. It is felt that, with the use of this technology, if the number of layers is increased, the production speed of wire material can be increased proportionately. The results will be announced at the International Superconducting Symposium held in Morioka City.

Additionally (27) in the area of oxide superconducting wire, Super-GM is also carrying out R&D using a variety of manufacturing methods to increase the current density of yttrium (Y), bismuth (Bi) and thallium (Th) materials, and make them into wires for use in electric power equipment. These efforts have resulted in the development of world-class superconducting wires, achieving a high-capacity 4-kA class Bi wire over 300-m long, and a Y wire with a high current density of 106 A/cm^3.

REFRIGERATION

Refrigeration design and cost has been identified by the principals in the SPI as one of the two key cost and reliability drivers in the decision process to commercialize superconducting products. Efficiency can vary dramatically (Carnot) based on the needed operating temperature of the superconducting device addressed, and the efficiency relates directly to cost of operation. At or below 4.2 K for example (liquid helium temperature), the Carnot efficiency is quite low. Theoretically, it takes approximately 75 W of refrigeration power to remove 1 W of heat from a 4 K environment, operating within a room temperature environment (47). Actual operating experience is even much more inefficient. “A typical helium liquefier may require 500-1000 W to remove 1 W of heat from 4 K to room temperature”(47). Even worse, the refrigeration devices which create ultra low temperatures such as 4 K tend to be very susceptible to contaminants which can shut down the system due to freezing and plugging of the tiny passageways inherent to these systems (Joule-Thompson plugs).

A tradeoff occurs in refrigeration design. Increased efficiency requires more complex and complicated systems with designs intent upon minimizing losses. This raises first cost, but lowers operating costs. Conversely, a lower first cost, simpler refrigeration system will probably require more expensive operation and maintenance costs. In either case, SPI principals indicate that the refrigeration technology for these products must be improved.

The Carnot efficiency of a refrigerator operating at 77 K (liquid nitrogen) is about 25 times better than one operating at 4 K. Therefore, the ability to operate at this higher temperature has inherent operating cost advantages, as well as allowing more simplicity of design incorporating higher reliability. There are even considerable advantages to operating at 20 K as opposed to 4 K (47).

Each different superconducting device design may require a different refrigeration design. The key parameters involved in any refrigeration decision include: operating temperature; cooling capacity; refrigerator efficiency; refrigerator capital cost; and refrigerator reliability, ease of operation, and safety (47). The superconductor in all large-scale superconducting devices must be maintained below the critical temperature. Open systems of refrigeration, where refrigerant (such as liquid nitrogen) is routinely resupplied, have the lowest initial cost, but high operation and maintenance costs. In devices requiring temperatures of 4 K, a Claude cycle refrigerator is used, incorporating a Joule-Thompson plug with very fine passages. The main failure mode of this system is from contamination closing the Joule-Thompson passages. Devices operating at higher temperatures (20 K and above) generally eliminate the need for a Joule-Thompson plug in the refrigeration system.

HTS devices are, at this point in time, expected to be cooled with closed-loop cryocoolers. This is a mature, highly reliable, and relatively low cost technology (47). "A prototype Stirling cryocooler...(built) to provide 250 W of cooling at 77 K demonstrated a maintenance interval in excess of 3,000 hours, had a mean-time-to-failure rate of 200,000 hours, and ran continuously for 50,000 hours (47). The disadvantage of cryocoolers, however, is their limited cooling capacity. At this point in time, there appears to be no commercially available, off-the-shelf, refrigeration systems that would readily match up to the superconducting product designs which are evolving. Therefore, it is expected that a new class of cryocooling refrigeration systems must be developed to accommodate these new products.

The primary disadvantage in using a gaseous cryogen for cooling is the loss of the isothermal behavior that is obtained with a liquid coolant at constant temperature. There is no latent heat of vaporization to absorb temperature transients. Therefore, the device must be of a design that can accommodate a range in operating temperature. The primary advantage of either gaseous or direct-conduction cooling is the potential for higher reliability (47).

Additionally, the Japanese have realized the importance of reliable and efficient refrigeration systems. The Japanese trade press (27) reports that a refrigeration system required for a superconducting generator was manufactured based on the results of component and system research, and was hooked up to the model superconducting generator and subjected to verification testing. These tests confirmed that this refrigeration system is capable of stable operation in a variety of operating modes (liquefaction, liquid storage, liquid delivery). In addition, this system was run for 3,000 hours in the liquefaction and liquid delivery modes at a liquid delivery volume of 100 liters/hour, which is the development objective, and an inert gas concentration of less than 0.1 ppm. It exhibited a mean time between failures of over 10,000 hours, proving itself to be highly reliable.

ENVIRONMENTAL BENEFITS

Environmental benefits from the installation of HTS technology accrue in two forms. First of all, the higher efficiency of electric generation, transmission, distribution, and utilization results in a lowered generated power requirement, resulting in lower greenhouse emissions to the atmosphere. Secondly, the highly efficient characteristics of HTS T&D make it more economically viable to generate electricity from renewable resources, in remote locations, and utilize the resultant generation in distant population centers.

Today, over 7.34% (and climbing) of all electricity generated is lost through T&D losses. Superconductive T&D could reduce this loss by about one-half. In the limit, this would mean electrical requirements could drop by about 3.67%, saving the associated 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 (13,48). Of this amount, 54% was coal-fired generation (35). 3.67% of this 54% 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 CO_2; 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 strongly 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 the 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 very 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 which this technology will bring will overcome a significant hindrance to wide renewables usage. HTS technology, clearly, 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 all available evidence, program plans, and insights. 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. If the high present prices are tied to fundamental materials costs, those are hard to lower, even though materials suppliers continue to be optimistic about further price decreases. If the high price is tied to manufacturing costs, then there is a further opportunity, since increased production and the associated increase in automation will cause total manufacturing costs to become substantially lower. 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:

________________GOVERNING FACTS AND ASSUMPTIONS

GOVERNING FACTS AND ASSUMPTIONS

The following is a list of assumptions and facts which form the basis of the analysis in this report.

1. Assumption: (Cases 1 and 2) EIA projects an average 0.9% drop per year from 1998 through 2020 (1). Actual average price figures used in this analysis may be found in Appendix II, Table II-1.

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 time 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 total generation less 7.34% lost in the transmission and distribution process (8,13). This has been the assumption for several years and is used in this analysis. However, recent data indicates that the grid may be becoming less efficient. Recent figures show a difference of 10.13% in 1997 and 11.05% in 1998 (1).

4. Fact: In 1997, total sales of electricity to ultimate customers was 3,140 billion kWh. In 1998, this rose to 3,240 BkWh (7). Total sales revenue was $215 billion in 1997 and $218 billion in 1998. Amount generated in 1998 was 3,620 billion kWh (1), which at an average value of 6.75 cents per kWh had a retail value of $244 billion.

5. Fact: Nonutility generation capacity was 12.6% the size of utility generation capacity at the end of 1998 (7). 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 (7).

6. Fact: Total installed "capability" (slightly different from capacity) in 1998 was 686,692 utility MW plus 98,085 nonutility MW for a total of 784,777 MW (1,7).

7. Assumption: From 1992 through 1998, net generation averaged annual increases of 2.5% (calculated from Table 8, Ref. 3 and Ref. 5). (Case 1) This annual rate of increase is projected to hold until affected by large market shares of HTS devices lessening waste, and therefore, lessening needed generation increases. (Case 2) The Energy Information Administration projects 1998 through 2020 increases averaging 1.4%. The EIA number is based on a 1% population growth and 1.9% industrial growth. For this analysis, both values are considered separately.

8. Fact: From 1992 through 1998, annual increases in generating capacity averaged 0.5% (calculated from Table 2, Ref.3) or remained flat (Table 1, 5). Clearly, capacity increases are not matching needed generation increases. Therefore, it is assumed that,

for the projection purposes of this report (Case 1), added capacity will average 2.5% per year in the time period of introduction of HTS devices. Since this is a "compounded" figure, to reach proper values for any given year, there is a multiple involved, applied to 1997 values, of $(1.025)^n$, where "n" is the number of years past 1997. 1998 becomes year 1 (n=1). In the EIA case (Case 2), the corresponding growth rate is 1.4% annually, resulting in a multiplier of $(1.014)^n$.

9. Fact: On a 1-to-1 substitution basis, HTS devices will save ½ of the energy losses in cables, electric motors, generators, and transformers (26). 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 (18). For the purpose of analysis, an even 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 (24).

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 (19).

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 well below maximum efficiency. Power transformers are responsible for 25% of all transmission/distribution losses (19), or $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 $8612.5 per mile per year. This is equivalent to saving ½ the presently lost power in underground cables (24).

14. Fact: 64% of all electrical power passes through electric motors, with ½ of this passing through large motors (13,6).

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 (100 hp 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 achieve a savings of 50% of presently wasted energy, considering the necessary cryogenic cooling inherent in the system.

16. Assumption: Generator losses are, similarly, expected to be cut by 50% when present systems are replaced by HTS technology systems.

17. Fact: Operating large electric motors (early HTS candidates) use 30% of all electricity generated in the U.S. (11). 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 (49).

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 (24).

19. Assumption: The annual growth rate in the cable market for HTS cable will be 3.4% per year (29).

20. Assumption: A cable demonstration project of at least 3-5 years will be required (37) 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 (29).

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 (28).

23. Fact: In any given year, 12% of the total population of all motors in the 5-500-hp class fail. Of these, ½ are rewound and ½ are replaced (Ref. 3, p. 3-19, 3-20). The replacement rate on large (>1000 hp) 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.

APPENDIX II:

TABLES USED FOR ANALYSIS

Table II-1. Electric growth and price multiples used for analysis.

Year	Case 1 Multiple $(1.025)^n$	Case 2 Multiple $(1.014)^n$	Case 1 and 2 Electric price (cents/kWh)
1998	1	1	6.75
2004	1.159	1.014	6.46
2005	1.189	1.102	6.40
2006	1.218	1.118	6.34
2007	1.249	1.133	6.28
2008	1.280	1.149	6.22
2009	1.312	1.165	6.16
2010	1.345	1.182	6.10
2011	1.379	1.198	6.04
2012	1.413	1.215	5.98
2013	1.448	1.232	5.92
2014	1.485	1.249	5.86
2015	1.522	1.267	5.80
2016	1.560	1.284	5.76
2017	1.599	1.302	5.72
2018	1.639	1.321	5.68
2019	1.680	1.339	5.64
2020	1.722	1.358	5.60

*From the DOE/EIA Annual Energy Outlook - 1999 (Ref. 4); Table A-8, Pg 124.

Table II-2. Total generation and installed transformer capacity.

Year	Total installed transformer capacity (10^6 MVA) Case 1	Total installed transformer capacity (10^6 MVA) Case 2	Total generation Case 1 (10^9 kWh)	Total generation Case 2 (10^9 kWh)
2004	2.908	2.639	3763	3414
2005	2.981	2.676	3857	3462
2006	3.056	2.713	3953	3510
2007	3.133	2.753	4052	3561
2008	3.212	2.790	4155	3610
2009	3.291	2.830	4257	3661
2010	3.372	2.869	4363	3712
2011	3.459	2.909	4474	3763
2012	3.545	2.951	4586	3817
2013	3.633	2.990	4700	3869
2014	3.724	3.032	4818	3923
2015	3.817	3.077	4938	3980
2016	3.913	3.119	5062	4034
2017	4.011	3.163	5188	4092
2018	4.111	3.207	5321	4149
2019	4.213	3.251	5451	4206
2020	4.318	3.298	5586	4266

APPENDIX III:

UTILITY SURVEY: OVERALL SUMMARY

UTILITY SURVEY: OVERALL SUMMARY

As a 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. Having 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 Califomia 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 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. As 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 that "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"

In our survey one of the questions 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 adapting 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" (lightening 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? _____%