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HIGH TEMPERATURE SUPERCONDUCTIVITY:

THE PRODUCTS AND THEIR BENEFITS

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Bob Lawrence & Associates, Inc.

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 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 1-28 and discussions with utility and technology experts. The Facts and Assumptions, then, drove the resulting analysis 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 underway to develop and commercialize HTS equipment in a time frame from the present to the year 2020. Based on technology status and perceived market advantages as determined from the references, market entry dates were projected followed by market penetration predictions. The earliest equipment to achieve commercialization is predicted to be fault current limiters, predicted for market entry in the 2003-2004 time period. 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:

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 - 1996 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 $564 million in 2010, $4.7 billion in 2015, and $17.6 billion in 2020. Cumulative benefits are $1.21 billion in 2010, $13.6 billion in 2015, and $72.5 billion in 2020. For Case 2 (the more conservative case), annual benefits become $412 million in 2010, $3.2 billion in 2015, and $11.1 billion in 2020. Cumulative benefits become $895 million in 2010, $9.42 billion in 2015, and $47.2 billion in 2020. For either case, the benefits of this technology are clearly substantial. All values are in constant 1996 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 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. 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 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, the temperature of liquid helium, is about 20 times that required to cool to 77 K which is the temperature of liquid nitrogen. Therefore, liquid helium costs about $5.00 per liter (1) whereas liquid nitrogen is only about 10 cents per liter. Thus, the major cost and energy advantage 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), 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" (2). Since superconducting wire is the main component of all superconducting cables, products, and systems, the price drop and performance increases projected by the Second Generation technology is highly significant and important to successful commercialization.

Transformer development is being carried out by the team of Waukesha Electric Systems, Intermagnetics General Corporation, Rochester Gas and Electric, Rensselaer Polytechnic Institute, and the Oak Ridge National Laboratory. This team has conducted a series of reference designs concentrating mostly on a 30-MVA, 138-kV/13.8-kV transformer which is representative of a class expected to capture "about half of all U.S. power transformer sales in the next two decades (3). According to Mehta et al. (3), Japan and Europe are somewhat ahead of the U.S. in transformer development.

> "In Japan, Kyushu University, Fuji Electric, and Sumitomo Electric Industries reported in August 1996 on a ....liquid nitrogen cooling approach....For their successful demonstration, they used 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."

> "In Europe, Asea Brown Boveri (ABB), American Superconductor Corporation, Electricite' de France, Services Industriels de Geneve, and the Ecole Polytechnique de Lausanne in March connected the world's first operational HTS distribution transformer, now powering the supply network of the city of Geneva."

In the U.S., under the Waukesha team, construction and preliminary testing of HTS transformer windings have been completed. The first complete system (1-MVA top rating, 13.8/6.9 kV, 20 K, single phase) has been assembled, and testing of that system has begun. The next step is a 5/10-MVA prototype transformer to power the Waukesha Electric Systems transformer manufacturing plant.

The U.S. HTS electric motor team is headed by the Reliance Electric Division of Rockwell Automation with American Superconductor Corporation as the HTS coil supplier and manufacturer. Also on this team are Centerior Energy (a utility company) and Sandia National Laboratory. "In February 1996, Reliance Electric successfully tested a four-pole, 1800-rpm synchronous motor using HTS windings operating at 27 K at a continuous 150-kW output. The coils...achieved currents of 100 A..., 25% over the initial goal of 80 A." (4). This program has now been extended to "develop a pre-commercial prototype of a 3.7-MW HTS motor." 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.

Generator efforts in the U.S., again, appear to be behind those in Japan. "The overall design approach (is) much the same for a superconducting generator as for a superconducting synchronous motor. The use of a superconducting rotor with conventional conductor in the stator gets around the problems connected with ac losses predicted with a superconducting stator" (4). In Japan, funds expended on LTS and HTS design, development, and demonstration were $75 million covering 1995 and 1996. This heavily funded effort, designated the Super-GM Program (standing for Engineering Research Association Project for Superconducting Generation Equipment and Materials) continues today with a high degree of visibility (5). The program involves 16 member organizations with representation from the electric utilities, manufacturers of electric power equipment, research organizations, manufacturers of LTS and HTS wire and tape, refrigeration and cryogenic suppliers, and independent research institutes. Three competing Japanese companies are supplying candidate superconducting rotors to be demonstrated in this program. The companies are Hitachi, Mitsubishi, and Toshiba. Testing of the three rotors is scheduled through 1998. The LTS conductor wire for the three rotors was supplied by Hitachi Cable, Sumitomo Electric, and Furukawa Electric, respectively. In the U.S., the DOE SPI program was supporting a team led by General Electric Company. This program was aimed at the conceptual design and assessment of a 100-MVA HTS generator and the development of a 100-MW "racetrack" coil. At this point in time, no full-scale precommercial demonstration is planned in the U.S.

Fault current limiters (FCLs) represent a new class of electric utility equipment with many attractive properties. This type of equipment may, in fact, be a market leader, since its properties appear to provide substantial potential cost savings to electric utilities as well as containing power outages. FCLs are devices which, under normal operating circumstances, act as if they are simply not there (superconducting). However, with a sudden current surge (such as caused by a shorted line), the limiter will develop a large impedance (like a resistance) to electrical current, keeping a power surge from exceeding design limits and protecting utility equipment, such as breakers, transformers, and generators, from fault current overload. Present designs appear to be able to implement high impedance within 1/2 a generating cycle (approximately 8 ms) affording excellent protection. Should the fault (or short) correct itself rapidly, the limiter will return to normal operation, and the whole sequence will do no harm to the device. In the U.S., the SPI team addressing FCLs is led by Lockheed Martin Corporation, and includes Southern California Edison, Intermagnetics General, and the Los Alamos National Laboratory. This team, from 1993-1995, successfully designed, built, and tested a prototype limiter rated at 2.4 kV, 3 kA (6). Scaleup is now occurring, leading to a precommercial unit rated at 15 kV, 20 kA which should be operational during 1998. The design of this unit is such that its operation should be that which was determined optimal during a detailed design and market study carried out by this team.

Foreign teams are also pursuing this potential product. In France, GEC-Alsthom is teamed with Electricité de France and, in Japan, Toshiba is teamed with Tokyo Electric.

Teams in Germany and Switzerland are also pursuing Fault Current Limiter concepts. Prototypes have been demonstrated and programs are moving forward.

Exciting developments have taken place in the field of underground HTS cables for T&D. In the U.S., two teams are pursuing two somewhat different technical concepts, but each team is led by a powerhouse electrical cable manufacturer. The team led by Pirelli North America is working on a concept identified by the term "warm dielectric." This design can carry twice the present current, in a cable of the same size as today's conventional technology, with only the present losses. A team led by the Southwire Company is developing an "all cryogenic" design, which should carry three to five times the current with 2/3 of the present losses. This latter concept is more expensive, but the benefits are significantly higher. Due to the benefits involved, Pirelli recently (February 1998) announced that they, too, were pursuing the “all cryogenic” concept. There is a tradeoff between the two concepts ---- the "warm dielectric" concept is especially well suited to replace conventional technology in existing American networks while the "all cryogenic" design is more suited to European and worldwide needs (7).

Foreign companies are also working hard on superconducting cable designs. In Japan, Tokyo Electric Power Company is teamed with Sumitomo Electric Industries, Ltd., and Furukawa Cabling System to develop a 6 kV, 1000 MVA HTS cable system with the vision of serving the needs of Tokyo and its growing population (7). In Europe, Siemens AG is working on developing a 100-m prototype for demonstration in 1999. In Denmark, NKT, a Danish cable manufacturer expects to test a three-phase prototype by the year 2000 and, in Britain, the British Insulated Cable Company is developing a prototype superconducting power cable. In this race, the U.S. is well positioned, with Southwire planning to demonstrate a 33-m, three-phase, 12.4 kV, 1250-A system by the end of 1999.

As is normal at the commercial beginning of a new, revolutionary technology, a market niche has been found for an initial product: Superconducting Magnetic Energy Storage Systems. These devices provide emergency power during momentary power cuts (1) by storing energy in the magnetic fields within them. Superconductivity, Inc., of Madison, Wisconsin, has sold a number of these systems at a price of about $1 million each, including one to South African Public Power Systems, Inc. (1). In 1998, Babcock and Wilcox is expected to complete a similar system for the Anchorage Municipal Power and Light utility in Alaska. It is a 0.5 MWh superconducting device costing $25 million. Both these applications use the older low temperature superconductors but Superconductivity, Inc., was recently purchased by American Superconductor and is expected to market a high temperature version as HTS conductor capabilities become commercially available.

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, 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 present average rate of 6.89 cents per kWh (9), this corresponds to retail level monetary savings of $8612.50 per mile per year.

The application of superconducting technology in generators, in 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 percent. Michael Kenward, in an article in Physics World (1) summarizes the projections made by various authors at the International Superconductivity Industrial Summit in May 1993. At that time, it was assumed that the global market for superconductors in the year 2000 would be $8-12 billion, followed by a rapid increase to $60-90 billion by 2010 and $150-200 billion by 2020. The technical item holding back this perceived market is the remaining need to "turn ceramics into robust components that can survive industrial manufacturing and assembly"(1).

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 (10). 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. 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 survey results taken during the past year, a prediction will be made as to the timing of 10% market share of each product, 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 1996 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" (11). 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 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 1995 was $10.4 billion, growing 8.6% over 1994. Electric Motors continue to increase as a percentage of electric energy use, moving from 53% of all electricity consumed in 1993 (11) to 64% in 1996 (9). As a percentage of total motor kWh, electric motors are distributed among residential (23%), commercial (20%), utilities (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 (11, 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 attractiveness of efficient motors over standard motors is increasing as may be seen from the following Table M-1 taken from Reference 13. The data is this table can be used to estimate the percent of efficient motor sales. From 1993 to 1995, efficient motors have increased market share from 19.2% to 20.3%. 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 11, 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 1995, total sales of electricity to ultimate customers was 3,013 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 x .64 x 3013) 1350 billion kWh (1995) 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 Laboratory. 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 (12). 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"(12). 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.

MARKET PENETRATION

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 remains a level 6.89 cents/kWh (Case 1) or declines by 1% per year (Case 2).

Therefore, benefits (kWh saved) are calculated as:

($3{,}013 \times 10^9$ kWh) × (Market Growth factor from 1995) × (.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	.390	.390	26.87	26.87
2007	2	.799	1.189	55.05	81.92
2008	3	1.23	2.42	84.75	166.74
2009	5	2.10	4.52	144.69	311.43
2010	7	3.01	7.53	207.39	518.82
2011	10	4.41	11.94	303.85	822.67
2012	15	6.78	18.72	467.14	1,290
2013	22	10.19	28.91	702.09	1,992
2014	31	14.72	43.63	1,014	3,006
2015	40	19.47	63.1	1,341	4,348
2016	50	24.95	88.05	1,719	6,067
2017	60	30.69	118.74	2,115	8,181
2018	68	35.65	154.39	2,456	10,637
2019	75	40.30	194.69	2,777	13,414
2020	79	43.50	238.19	2,997	16,411

Case 1 shows that by 2010, HTS motors will save a cumulative 16.05 billion kWh equivalent to $1.106 billion. By 2015, this becomes 182.35 billion kWh or $12.564 billion. And finally, by the end of 2020, this technology will have saved a cumulative 976.41 billion kWh or $67.274 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	.346	.346	20.97	20.97
2007	2	.702	1.048	42.26	63.23
2008	3	1.07	2.118	63.99	127.22
2009	5	1.80	3.918	106.92	234.14
2010	7	2.56	6.478	151.04	385.18
2011	10	3.71	10.19	216.67	601.85
2012	15	5.64	15.53	326.00	927.85
2013	22	8.39	23.92	479.91	1,408
2014	31	11.99	35.91	678.63	2,087
2015	40	15.69	51.6	878.64	2,966
2016	50	19.88	71.48	1,109	4,075
2017	60	24.2	95.68	1,346	5,421
2018	68	27.81	123.49	1,541	6,962
2019	75	31.10	154.59	1,717	8,679
2020	79	33.22	187.81	1,830	10,509

Case 2 indicates that by 2010, HTS motors will save a cumulative 13.91 billion kWh equivalent to $0.8307 billion. By 2015, this becomes 151.06 billion kWh or $8.821 billion. And finally, by the end of 2020, this technology will have saved a cumulative 784.11 billion kWh or $44.467 billion.

TRANSFORMERS

THE MARKET

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 megavolt-ampere (MVA) of generating capacity there are 3 to 4 MVA of transformer in place (14). 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 (3). 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 (3), 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" (3). These authors note that the use of HTS windings may "soon turn power transformers into compact high-performers on good terms with the environment."

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 an 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?" <u>The top concern</u> 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

According to Mehta et al (3), 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.

In the U.S., the first operational demonstration of an HTS technology transformer is just beginning. Development is being carried out by the team of Waukesha Electric Systems, Intermagnetics General Corporation, Rochester Gas and Electric, Rensselaer Polytechnic Institute, and the ORNL. 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.

In the U.S., the first complete system has been assembled, and testing of that system has begun. The next step is a 5-MVA prototype transformer to power the Waukesha Electric

Systems transformer manufacturing plant. This is still below the 30-MVA size that represents half the expected market, but the technology experience should be readily scaled upwards to 30 MVA. The 5-MVA program is to be completed by September 1999 after which a 30-MVA "beta prototype" will be designed, built, and installed at a utility test site (15). "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.

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 776,335 MW (1995) multiplied by 3 equals 2,329,005 MVA (1995). 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 67,541 MVA per year (Case 1) or 54,732 MVA per year (Case 2) based on 1995 generation. Consistent with the estimates of Mehta et al. (3), this is the equivalent of approximately 2251, 30-MVA transformers (Case 1) or 1824, 30-MVA transformers (Case 2). This target market, then, grows from 1995 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 (8,9). 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	20.53	20.53	1.41	1,729
2006	2	42.08	62.61	4.31	3,458
2007	3	64.68	127.29	8.77	5,451
2008	5	110.55	237.84	16.39	9,315
2009	7	158.55	396.39	27.31	13,361
2010	10	232.2	628.59	43.31	19,558
2011	15	357.15	985.74	67.92	30,093
2012	22	536.8	1523	104.93	45,234
2013	31	775.31	2298	158.33	65,321
2014	40	1026	3324	229.02	86,397
2015	50	1314	4638	319.56	110,693
2016	59	1589	6627	456.6	133,903
2017	66	1822	8049	554.58	153,541
2018	71	2011	10060	693.13	169,291
2019	74	2147	12207	841.06	180,822
2020	76	2259	14466	996.71	190,337

Therefore, by 2010, a total accumulated benefit of $101.5 million should occur from the commercialization of HTS transformers according to present projections. By 2015, this grows to $981 million, and by 2020, it is $4.523 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	14.93	14.93	.91	1257
2006	2	30.27	45.20	2.74	2550
2007	3	46.07	91.27	5.49	3882
2008	5	77.84	169.11	10.11	6557
2009	7	110.51	279.62	16.61	9311
2010	10	160.07	439.69	25.94	13,484
2011	15	243.4	683.09	39.89	20,508
2012	22	362.12	1045	60.40	30,513
2013	31	517.21	1562	89.35	43,564
2014	40	676.68	2239	126.73	57,002
2015	50	858.14	3097	173.43	72,310
2016	59	1026	4123	230.06	86,490
2017	66	1165	5288	294.01	98,116
2018	71	1270	6558	363.31	107,018
2019	74	1342	7900	436.08	113,070
2020	76	1398	9298	512.32	117,805

In Case 2, by 2010, a total accumulated benefit of \$61.8 million should occur from the commercialization of HTS transformers according to present projections. By 2015, this grows to \$551.6 million and, by 2020, it is \$2.387 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 generators are considered to be a potential market. Even nonutility generators are considered too small to be an early, predictable market. Therefore, the overall market addressed, from our list of assumptions, is the in-place and growing utility generation market which was 706,111 utility megawatts (9,13) in 1995. From the list of facts and assumptions (Appendix I), utility power generated in that year was 2,975 kWh at a value of $205 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 (16). 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 (17), 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 (4), 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. A report generated by Dr. Christine Platt of DOE and C. A. Matzdorf of Energetics, Inc., describes the present status of the HTS generator effort in the U.S., funded by the DOE through it's Superconductivity Partnership Initiative (18). In this paper, Platt and Matzdorf describe the 100-MVA generator project as follows:

> The 100 MVA HTS generator project team, led by General Electric Company (GE), plans to deliver a commercial product that is more that 50% smaller and operates with half of the efficiency losses of a conventional generator of the same rating. GE hopes commercialization will lead to extensive retrofits to existing generators along with new generator sales in the international market. Team members include Intermagnetics General Corporation, Niagara Mohawk Power Corporation, New York State Energy Research and Development Authority, the New York State Institute on Superconductivity, and Argonne, Los Alamos, and Oak Ridge National Laboratories. The Phase I goal of the generator team is to build and test a 100 MVA generator coil subset and design a 100 MVA HTS generator. The team has completed the preliminary generator design and continues to study power system interaction.

Probably the most advanced HTS generator development program in the world is under way in Japan. Paraphrasing Blaugher (4), The Engineering Research Association for Superconducting Generation Equipment and Materials (Super-GM) was started in 1987. The team members include Hitachi, Mitsubishi Electric, and Toshiba. Last year, this program began the final stage of testing a 70 MW superconducting generator with three different rotors, each constructed by a different team member. This program will be finished at the end of 1998. The next phase will be the design and construction of a 200 MW - class generator, seen as a commercial "pilot."

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

The Nikkei article 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 (1995 values), fully installed HTS generators (utility and nonutility) would save \$2.24 billion per year (1% of total generation) based on numbers for 1995. The total market to be addressed is the utility (only) market, with an ultimate savings of \$2.05 billion (1995 numbers). 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 utility capacity annually. This equates to 4.5% × 706,111 MW or 31,775 MW annually based on 1995 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 24,008 MW (1995). Per sales year, implemented, retail value, electric savings become:

Case 1: (4.5%) × (\$2.05B) × ($[1.025]^n$) × (percent market penetration)
Case 2: (3.4%) × (\$2.05B) × ($[1.014]^n$) × (percent market penetration) × ($[0.99]^n$)

In case 2, the factor $(0.99)^n$ must be applied, as EIA estimates a 1% 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	1.37	1.37
2012	2	.090	2.81	4.18
2013	3	.135	4.32	8.50
2014	5	.225	7.38	15.88
2015	7	.315	10.58	26.46
2016	10	.450	15.50	41.96
2017	15	.675	23.83	65.79
2018	22	.990	35.82	101.61
2019	31	1.40	51.73	153.34
2020	40	1.80	68.41	221.75
2021	50	2.25	87.65	309.40

Although the benefits from generators are less than from motors or transformers, they are clearly significant accumulating to $950 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	0.73	0.73
2012	2	.068	1.47	2.20
2013	3	.102	2.22	4.42
2014	5	.170	3.71	8.13
2015	7	.238	5.22	13.35
2016	10	.340	7.48	20.83
2017	15	.510	11.27	32.10
2018	22	.748	16.59	48.69
2019	31	1.054	23.46	72.15
2020	40	1.360	30.40	102.55
2021	50	1.700	38.14	140.69

In Case 2, the benefits from generators are considerably less than in Case 1, but they are still significant, accumulating to $446 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 (19). The annual growth rate in the cable market for HTS cable will be 3.4% per year (20). A cable demonstration project of at least 4 years will be required (20). 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 (20). 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 (16).

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

In the U.S., the world's two largest cable manufacturers, Southwire and Pirelli, are both involved in developing potential HTS cable products. Southwire heads a team of ORNL, Los Alamos, Argonne, and a utility company partner. Pirelli is working with the Electric Power Research Institute (EPRI), American Superconductor Corporation, and the Los Alamos and Oak Ridge National Laboratories. According to Dr. Paul Grant of EPRI, Pirelli has successfully constructed and tested a 50-m underground transmission cable containing more than six kilometers of lead-stabilized BSCCO tape (21). 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 (7). In Germany, Siemens is working on "the first serially produced superconducting cable for 110 kilovolt service (to be ready) in late 1998." (24) The cable will be 50-m long.

The Southwire effort to get to commercialization consists of three phases (22). 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.

MARKET PENETRATION

Phase II will be completed in the year 2000, leading to the multi-unit demonstration. The Pirelli program, the Siemens 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 ($8,613) × (total miles).
>
> Case 2: (% Market Penetration) × (158 miles) × ($[1.014]^n$), and dollar savings will be ($8,613) × (total miles) × ([0.99]n). Again, Case 2 (the EIA case) assumes a price of electricity decline averaging 1% 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 (20).

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	.059
2006	6.7	13.89	20.76	.179
2007	10.0	21.25	42.01	.362
2008	15.0	32.68	74.69	.643
2009	21.0	46.88	121.57	1.047
2010	27.0	61.77	183.34	1.579
2011	33.0	77.43	260.77	2.246
2012	40.0	96.19	356.96	3.074
2013	48.0	118.31	475.27	4.094
2014	56.0	141.47	616.75	5.312
2015	63.0	163.15	779.90	6.717
2016	69.0	183.15	963.05	8.295
2017	74.0	201.34	1,164	10.029
2018	77.0	214.73	1,379	11.875
2019	79.0	225.80	1,605	13.822
2020	80.0	234.35	1,839	15.842

For Case 1, total accumulated savings through the year 2020 will be $85 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	.047
2006	6.7	12.33	18.42	.141
2007	10.0	18.68	37.10	.280
2008	15.0	28.39	65.49	.490
2009	21.0	40.31	105.8	.784
2010	27.0	52.56	158.36	1.161
2011	33.0	65.12	223.48	1.622
2012	40.0	80.07	303.55	2.182
2013	48.0	97.38	400.93	2.853
2014	56.0	115.2	516.13	3.636
2015	63.0	131.49	647.62	4.516
2016	69.0	145.98	793.6	5.479
2017	74.0	158.78	952.38	6.510
2018	77.0	167.53	1120	7.579
2019	79.0	174.25	1294	8.670
2020	80.0	178.98	1473	9.769

For Case 2, total accumulated savings through the year 2020 will be $55.7 million.

FAULT CURRENT LIMITERS

THE MARKET

Fault current limiters (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 (6), 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 16ms); provide immediate (within a half-cycle, or 8ms) recovery to normal operation after the clearing of a fault; be capable of addressing two faults within a period of 15 seconds; and be compact, lightweight, inexpensive, fully automatic, and highly reliable with a long lifetime (6).

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 (23) 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:

Under the DOE's SPI, a team has formed to address a 2.4-kV FCL concept. The team consists of Lockheed Martin Corporation, American Superconductor Corporation, Southern California Edison Company, and Los Alamos National Laboratory. 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 (23). 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 seconds, as well as the other market needs previously mentioned. By reducing the maximum fault currents well below those presently experienced, it has the potential to eliminate the need for premature replacement of circuit breakers, buses, disconnects, wave traps, transformers, etc.

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 ($ $\times 10^6$).

Year	Motors	Transformers	Generators	Cable	Total
2004	0	0	0	0	0
2005	0	1.41	0	.059	1.47
2006	26.87	4.31	0	.179	31.36
2007	81.92	8.77	0	.362	91.05
2008	166.74	16.39	0	.643	183.77
2009	311.43	27.31	0	1.047	339.79
2010	518.82	43.31	0	1.579	563.71
2011	822.67	67.92	1.37	2.246	894.21
2012	1,290	104.93	4.18	3.074	1,402
2013	1,992	158.33	8.50	4.094	2,163
2014	3,006	229.02	15.88	5.312	3,256
2015	4,348	319.56	26.46	6.717	4,700
2016	6,067	456.6	41.96	8.295	6,574
2017	8,181	554.58	65.79	10.029	8,811
2018	10,637	693.13	101.61	11.875	11,444
2019	13,414	841.06	153.34	13.822	14,422
2020	16,411	996.71	221.75	15.842	17,645

In Case 1, by the end of 2010, benefits are projected to accrue totaling $1.21 billion. By the end of 2015, total accrued benefits become $13.6 billion and by 2020, the accrued benefit is $72.5 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	.91	0	.047	.957
2006	20.97	2.74	0	.141	23.85
2007	63.23	5.49	0	.280	69.00
2008	127.22	10.11	0	.490	137.82
2009	234.14	16.61	0	.784	251.53
2010	385.18	25.94	0	1.161	412.28
2011	601.85	39.89	0.73	1.622	644.09
2012	927.85	60.40	2.20	2.182	992.63
2013	1,408	89.35	4.42	2.853	1,505
2014	2,087	126.73	8.13	3.636	2,225
2015	2,966	173.43	13.35	4.516	3,157
2016	4,075	230.06	20.83	5.479	4,331
2017	5,421	294.01	32.10	6.510	5,754
2018	6,962	363.31	48.69	7.579	7,382
2019	8,679	436.08	72.15	8.670	9,196
2020	10,509	512.32	102.55	9.769	11,134

In Case 2 (using EIA projections), by the end of 2010, benefits are projected to accrue totaling $895 million. By the end of 2015, total accrued benefits become $9.42 billion, and by 2020, the accrued benefit is $47.22 billion. Clearly, even this highly conservative analysis shows that substantial national benefits can accrue from this technology, expanding greatly into the 21st century.

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, about 7.34% 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 (9,13). Of this amount, 54% was coal-fired generation (24). 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; 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

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

1. Assumption: (Case 1) The average retail price of electricity will remain at 6.89 cents per kWh for the foreseeable future (1995 dollars). The average retail price of electricity in 1995 was 6.89 cents per kWh (9). The EIA reports that the average retail price went down from 1994 to 1995; from 6.91 cents to 6.89 cents. While the average price may remain constant or decrease slightly, the nationwide spread in price may decrease; i.e., deregulation may level the playing field between regions on a nationwide basis. With the tremendous number of unknowns being introduced into the electric utility market by restructuring, it is very hard to make any assumption at all regarding future average retail prices. California is now proving this. Assuming a continuing downward pressure on prices, however, the projection forward of 6.89 cents seems to be as good an assumption as any. (Case 2) EIA projects an average 1% drop per year from 1996 through 2020 (24).

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 (8,9).

4. Fact: In 1995, total sales of electricity to ultimate customers was 3,013 billion kWh (9). At 6.89 cents per kWh, this amounts to total sales revenue of $208 billion. Amount generated was 3,252 billion kWh (9,13) with a retail value of $224 billion.

5. Fact: Nonutility generation capacity was 9.3% the size of utility generation capacity in 1995 (13). This amounted to 70,254 MW counting only the total installed capacity of nonutility power producers with an installed capacity of 1 MW or more.

6. Fact: Total installed capacity in 1995 was 706,111 utility MW plus 70,254 nonutility MW for a total of 776,365 MW (9,13).

7. Assumption: From 1992 through 1995, net generation averaged annual increases of 2.5% (calculated from Table 8, Ref. 2). (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 1996 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 1995, annual increases in generating capacity averaged 0.5% (calculated from Table 2, Ref.2). 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 1995 values, of $(1.025)^n$, where "n" is the number of years past 1995. In the EIA case based on the values calculated in the Annual Energy Outlook 1998 (24), the corresponding growth rate is 1.4% annually, resulting in a multiplier of $(1.014)^n$ (Case 2).

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 (4). 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 (14). 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 (16).

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 (3).

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 (3), 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 (16).

14. Fact: 64% of all electrical power passes through electric motors, with ½ of this passing through large motors (9).

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 25% of all electricity generated in the U.S. (16). This is the equivalent of $52 billion in retail sales of 1995 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 (25).

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 (16).

19. Assumption: The annual growth rate in the cable market for HTS cable will be 3.4% per year (20).

20. Assumption: A cable demonstration project of at least 4 years will be required (20) 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 (20).

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 (19).

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. 2, 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

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 2* Electric price (cents/kWh)
1995	1	1	7.00
2004	1.249	1.133	6.16
2005	1.280	1.149	6.10
2006	1.312	1.165	6.06
2007	1.345	1.182	6.02
2008	1.379	1.198	5.98
2009	1.413	1.215	5.94
2010	1.448	1.232	5.90
2011	1.485	1.249	5.84
2012	1.522	1.267	5.78
2013	1.560	1.284	5.72
2014	1.599	1.302	5.66
2015	1.639	1.321	5.60
2016	1.680	1.339	5.58
2017	1.722	1.358	5.56
2018	1.765	1.377	5.54
2019	1.809	1.396	5.52
2020	1.854	1.416	5.51

*From the DOE/EIA Annual Energy Outlook - 1998 (Ref. 28); Table A-8, Pg 112.

APPENDIX III

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

OVERALL IMPRESSIONS

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

ISSUE: "HTS IS EXPENSIVE"

Regardless of the degree to which engineers supported HTS, most expressed concern over the perceived high cost of HTS as compared with conventional technologies, particularly in view of the increasing importance of initial capital costs in a competitive market. The 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

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? _____%