World Technology Evaluation Center

WTEC

WTEC Panel Report on

POWER APPLICATIONS OF SUPERCONDUCTIVITY IN JAPAN AND GERMANY

David Larbalestier, Panel Chair
Richard D. Blaugher
Robert E. Schwall
Robert S. Sokolowski
Masaki Suenaga
Jeffrey O. Willis

September 1997

International Technology Research Institute
R.D. Shelton, Director
Geoffrey M. Holdridge, WTEC Director

Loyola College in Maryland
4501 North Charles Street
Baltimore, Maryland 21210-2699

WTEC PANEL ON POWER APPLICATIONS OF SUPERCONDUCTIVITY IN JAPAN AND GERMANY

Sponsored by the National Science Foundation and the Department of Energy of the United States Government

David Larbalestier (Panel Chair)
University of Wisconsin
Applied Superconductivity Center
Room 915
1500 Engineering Drive
Madison, WI 53706

Richard Blaugher
National Renewable Energy Lab.
Midwest Research Institute
1617 Cole Blvd.
Golden, CO 80401

Robert Schwall
American Superconductor Corp.
2 Technology Drive
Westborough, MA 01581

Robert Sokolowski
IGC Advanced Superconductors
1875 Thomaston Avenue
Waterbury, CT 06704

Masaki Suenaga
Brookhaven National Lab.
Bldg. 480
Upton, NY 11973

Jeffrey Willis
Mail Stop K763; STC
Los Alamos National Laboratory
Los Alamos, NM 87545

INTERNATIONAL TECHNOLOGY RESEARCH INSTITUTE WTEC PROGRAM

The World Technology Evaluation Center (WTEC) at Loyola College (previously known as the Japanese Technology Evaluation Center, JTEC) provides assessments of foreign research and development in selected technologies under a cooperative agreement with the National Science Foundation (NSF). Loyola's International Technology Research Institute (ITRI), R.D. Shelton, Director, is the umbrella organization for WTEC. Paul Herer, Senior Advisor for Planning and Technology Evaluation at NSF's Engineering Directorate, is NSF Program Director for WTEC. Other U.S. government agencies that provide support for the program include the National Aeronautics and Space Administration, the Department of Energy, the Department of Commerce, and the Department of Defense.

WTEC's mission is to inform U.S. policy makers, strategic planners, and managers of the state of selected technologies in foreign countries in comparison to the United States. WTEC assessments cover basic research, advanced development, and applications/commercialization. Small panels of about six technical experts conduct WTEC assessments. Panelists are leading authorities in their field, technically active, and knowledgeable about U.S. and foreign research programs. As part of the assessment process, panels visit and carry out extensive discussions with foreign scientists and engineers in universities and in industry/government labs.

The ITRI staff at Loyola College help select topics, recruit expert panelists, arrange study visits to foreign laboratories, organize workshop presentations, and finally, edit and disseminate the final reports.

Dr. R.D. Shelton
Principal Investigator
Loyola College
Baltimore, MD 21210

Mr. Geoff Holdridge
WTEC Director
Loyola College
Baltimore, MD 21210

Dr. George Gamota
TTEC Director
17 Solomon Pierce Road
Lexington, MA 02173

WTEC Panel on

POWER APPLICATIONS OF SUPERCONDUCTIVITY IN JAPAN AND GERMANY

FINAL REPORT

September 1997

David Larbalestier, Panel Chair
Richard D. Blaugher
Robert E. Schwall
Robert S. Sokolowski
Masaki Suenaga
Jeffrey O. Willis

ISBN 1-883712-46-7
This document was sponsored by the National Science Foundation (NSF) and the Department of Energy (DOE) under NSF Cooperative Agreement ENG-9416970, awarded to the International Technology Research Institute at Loyola College in Maryland.

ABSTRACT

This report reviews the status of research and development (R&D) on electric utility and other high-power applications of superconducting materials in Japan, Germany, and to a limited extent other countries in Western Europe. WTEC will publish a companion volume shortly covering electronic applications of superconductivity in Japan. This report compares activities abroad with those in the United States, and includes a brief overview of the U.S. Department of Energy's program in this area. The focus of the study is on high temperature (HTS) superconductors (i.e., those that show superconducting properties at temperatures above the boiling point of liquid nitrogen), although the WTEC panel also looked at applications for low-temperature (LTS) materials. The report covers government funding for power applications of superconductivity and compares the roles of public organizations, industry, and academia in this field among the countries of interest. The panel concluded that the United States is behind Japan in BSCCO-2212 tapes. It is holding level with Germany and Japan with respect to biaxially textured YBCO tapes, and is holding level with Japan in the area of BSCCO-2223 and Tl-1223 conductors. The United States leads Germany in conductors made from BSCCO-2212 and -2223 and from Tl-1223. In the applications area, the panel found that the United States is behind Japan in generators, magnetic levitation, and fault current limiters, and is trailing Europe in transformers. U.S. systems technology is level with that of Japan in current leads, power cables, transformers, and flywheels, and is leading Japan and Germany in motors and superconducting magnetic energy storage (SMES). The United States is also leading Germany in the areas of power cables, current leads, and fault current limiters. Both Germany and Japan continue to invest substantial resources in LTS R&D. The panel found that both the Japanese and German superconductivity R&D programs enjoy strong, enduring commitments from government and large companies, motivated by a vision of superconductivity as a key enabling technology for the next century. U.S. R&D, on the other hand, is more subject to changing federal budget priorities from year to year; however, the Department of Energy recently received a substantial funding increase for its FY 1998 R&D program in this area.

International Technology Research Institute (ITRI)
World Technology Evaluation Center (WTEC)

R. D. Shelton, Principal Investigator, ITRI Director
George Gamota, TTEC Director
Geoffrey M. Holdridge, WTEC Director
Bobby A. Williams, WTEC Deputy Director
Aminah Batta, Editorial Assistant
Catrina M. Foley, Administrative Assistant
Christopher McClintick, Research Associate
Roan E. Horning, Professional Assistant
Michael Stone, Student Assistant
Jason Ruggieri, Student Assistant

Patricia M.H. Johnson, Editor

Cecil Uyehara, Senior Advisor for Japan Operations
Hiroshi Morishita, WTEC Japan Representative

The ISBN number for this report is 1-883712-46-7. This report is distributed by the National Technical Information Service (NTIS) of the U.S. Department of Commerce as NTIS report # PB98-103161. A list of available JTEC/WTEC reports and information on ordering them from NTIS is included on the inside back cover of this report.

FOREWORD

The National Science Foundation (NSF) has been involved in funding technology assessments comparing the United States and foreign countries since 1983. A sizable proportion of this activity has been in the Japanese Technology Evaluation Center (JTEC) and World Technology Evaluation Center (WTEC) programs. NSF has supported more than 40 JTEC and WTEC studies over a wide range of technical topics. Both programs are now subsumed under the single name, WTEC, although the JTEC name has remained until recently on reports that cover only Japan.

As U.S. scientific and technological leadership is challenged in areas of previous dominance such as aeronautics, space, and nuclear power, many governmental and private organizations seek to set policies that will help maintain U.S. strengths. To do this effectively requires an understanding of the relative position of the United States and other countries. The purpose of the WTEC program is to assess research and development efforts in other countries in specific areas of technology, to compare these efforts and their results to U.S. research in the same areas, and to identify opportunities for international collaboration in precompetitive research.

Many U.S. organizations support substantial data gathering and analysis efforts directed at nations such as Japan. But often the results of these studies are not widely available. At the same time, government and privately sponsored studies that are in the public domain tend to be "input" studies; that is, they provide enumeration of inputs to the research and development process, such as monetary expenditures, personnel data, and facilities, but do not provide an assessment of the quality or quantity of the outputs obtained.

Studies of the outputs of the research and development process are more difficult to perform because they require a subjective analysis performed by individuals who are experts in the relevant technical fields. The NSF staff includes professionals with expertise in a wide range of disciplines. These individuals provide the technical expertise needed to assemble panels of experts who can perform competent, unbiased, technical reviews of research and development activities.

Specific technologies, such as telecommunications, biotechnology, microelectromechanical systems, and advanced materials, are selected for study by government agencies that have an interest in obtaining the results of an assessment and are able to contribute to its funding. A typical assessment is sponsored by two to four agencies. In the first few years of the program, most of the studies focused on Japan, reflecting concern over Japan’s growing economic prowess.

Beginning in 1990, we began to broaden the geographic focus of the studies. As interest in the European Community (now the European Union) grew, we added Europe as an area of study. With the breakup of the former Soviet Union, we began organizing visits to previously restricted research sites opening up there. These most recent WTEC studies have focused on identifying opportunities for cooperation with researchers and institutes in Russia, the Ukraine, and Belarus, rather than on assessing them from a competitive viewpoint. Most recently, studies have begun to focus also on emerging technological powers in Asia.

In the past several years, we also have begun to substantially expand our efforts to disseminate information. Attendance at WTEC workshops (in which panels present preliminary findings) has increased, especially industry participation. Representatives of U.S. industry now routinely number 50% or more of the total attendance, with a broad cross-section of government and academic representatives making up the remainder. Publications by WTEC panel members based on our studies have increased, as have the number of presentations by panelists at professional society meetings.

The WTEC program will continue to evolve in response to changing conditions in the years to come. We are now implementing initiatives aimed at the following objectives:

- Disseminating the results of WTEC studies via the Internet. Seventeen of the most recent WTEC final reports are now available on the World Wide Web (http://itri.loyola.edu) or via anonymous FTP (ftp.wtec.loyola.edu/pub/). Viewgraphs from several recent workshops are also on the Web server.

- Expanding opportunities for the larger science and technology community to help define and organize studies
- Increasing industry sponsorship of WTEC studies

The latter two objectives are now being served under the WTEC Community-Initiated State-of-the-Art Reviews (CISAR) initiative. CISAR provides an opportunity for the U.S. R&D community to suggest and carry out studies that might not otherwise be funded solely at the initiative of the government. For example, WTEC has formed partnerships with university/industry teams, with partial funding from industry, to carry out three CISAR studies, covering the Korean semiconductor industry, electronics final assembly technologies in Pacific Rim countries, and civil infrastructure technologies in Pacific Rim countries, respectively. Several other topics are under consideration. Further information on the CISAR initiative is available on the WTEC WWW server (http://itri.loyola.edu/cisar.htm) or by contacting the WTEC office.

In the end, all government-funded programs must answer the question, How has this investment benefited the nation? A few of the benefits of the WTEC program follow:

- JTEC studies have contributed significantly to U.S. benchmarking of the growing prowess of Japan's technological enterprise. Some have estimated that JTEC has been responsible for over half the major Japanese technology benchmarking studies conducted in the United States in the past decade. JTEC and WTEC reports have also been widely cited in various competitiveness studies.
- These studies have provided important input to policy makers in federal mission agencies. JTEC and WTEC panel chairs have given special briefings to senior officials of the Department of Energy and Commerce, to the National Aeronautics and Space Administration (NASA) administrator, and to the President's science advisor. Two recent studies on electronic packaging and related electronics manufacturing issues have had a particularly significant impact in this regard. The 1995 JTEC report on electronic manufacturing and packaging in Japan was cited by the Defense Secretary and the Commerce Secretary in a joint announcement of a $30-40 million government initiative to improve U.S. competitiveness in electronic packaging. The President's Office of Science and Technology Policy and two senior officials at the Department of Commerce have received briefings on a follow-on WTEC study covering electronic manufacturing in other Pacific Rim countries.
- Studies have been of keen interest to U.S. industry, providing managers with a sense of the competitive environment internationally. The director for external technology at a major U.S. high-technology firm recently told us that that he always looks for a relevant WTEC report first when beginning to investigate a technology for his company, because these reports provide a comprehensive understanding that includes R&D, process technology, and some information on commercial developments. The list of corporate users of the WTEC World Wide Web server includes virtually all of the nation's high-technology sector.

Not the least important is the educational benefit of the studies. Since 1983 over 200 scientists and engineers have participated as panelists in the studies. As a result of their experiences, many have changed their viewpoints on the significance and originality of foreign research. Some have also developed lasting relationships and ongoing exchanges of information with their foreign hosts as a result of their participation in these studies.

As we seek to refine the WTEC program in the coming years, improving the methodology and enhancing the impact, program organizers and participants will continue to operate from the same basic premise that has been behind the program from its inception: the United States can benefit from a better understanding of cutting-edge research that is being conducted outside its borders. Improved awareness of international developments can significantly enhance the scope and effectiveness of international collaboration and thus benefit all of the United States' international partners in collaborative research and development efforts.

Paul J. Herer
National Science Foundation
Arlington, VA

TABLE OF CONTENTS

4. **Power Systems — Other Applications**
Robert Schwall

5. **HTS Conductor Technology**
Jeffrey O. Willis

6. **Low T_c Superconductor R&D in Japan**
Masaki Suenaga

APPENDICES

C. **Japanese Site Reports**

D. **European Site Reports**

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

BACKGROUND

In early 1996, the U.S. Department of Energy and National Science Foundation asked the World Technology Evaluation Center (WTEC) to assemble a panel to assess, relative to the United States, how Japan and Germany are responding to the challenge of applying superconductivity to power and energy applications. Although the study was focused mostly on the impact of high temperature superconductors (HTS) on the power applications field, the WTEC panel also looked at many applications for low temperature superconductors (LTS). The market for low temperature superconductor applications is well established, as is that for superconducting electronics, for which there is a separate WTEC panel.[1] The panel on power applications of superconductivity was commissioned to identify the roles of public organizations, industry, and academia for advancing power applications of superconductivity, taking both a present and a long-term view.

The study was carried out by a panel of leading U.S. experts in the field. (See Chapter 1 and Appendices A and B for biographies of panelists and other team members). The panel reviewed the relevant literature, then made a one-week trip to Japan to visit sites where work in this field is underway. A subset of panelists then continued on for a week of site visits in Germany and Switzerland. Chapter 1 describes the visits briefly. A complete set of site reports is included in Appendices C (Japan) and D (Europe). The panel presented preliminary findings at a workshop in Washington, DC, in July 1996. Based on its findings and on feedback from workshop participants, the panel then drafted this written report. The draft report was reviewed by Japanese and German hosts as well as by sponsors prior to publication.

SUMMARY OF FINDINGS

Tables ES.1 and ES.2 present the WTEC panel's best assessment of the U.S. program strengths and weaknesses in high T_c conductors and systems technologies as compared to those of Japan and Germany. The United States leads Germany in conductors made from BSCCO-2212 and -2223 and from Tl-1223.[2] It is holding level with Germany and Japan with respect to biaxially textured YBCO tapes[2] and is holding level with Japan in the area of BSCCO-2223 and Tl-1223 conductors. It lags Japan in the area of BSCCO-2212 tapes.

A particular strength of the Japanese program is that it is enduring. It has strong commitments from government, large multinational companies, utilities, and to a lesser extent, from universities. A cornerstone of Japan's present program is Super-GM, a large-scale national generator and materials development program. Amplifying Japan's national effort is the work of the International Superconductivity Technology Center (ISTEC), whose principal goal has been to develop the materials aspects of HTS. The Japanese program is now the largest worldwide, by about a factor of two as judged by the data in Fig. ES.1. Part of the reason for the larger size of Japan's program is that it is much more involved with LTS conductors than either the U.S. or the German program. This reflects the belief prevalent in Japan's scientific community that the real payoff for superconductivity will come in the twenty-first century, so that it does not greatly matter whether devices built today use LTS or HTS materials, provided no barrier is created to using whichever materials system will make the device more attractive when the market does arrive.

---

[1] The report of the WTEC Panel on Electronic Applications of Superconductivity in Japan will be published later in 1997.

[2] See glossary, Appendix F, for the formulas of the acronyms for common classes of high-temperature superconducting compounds discussed in this report.

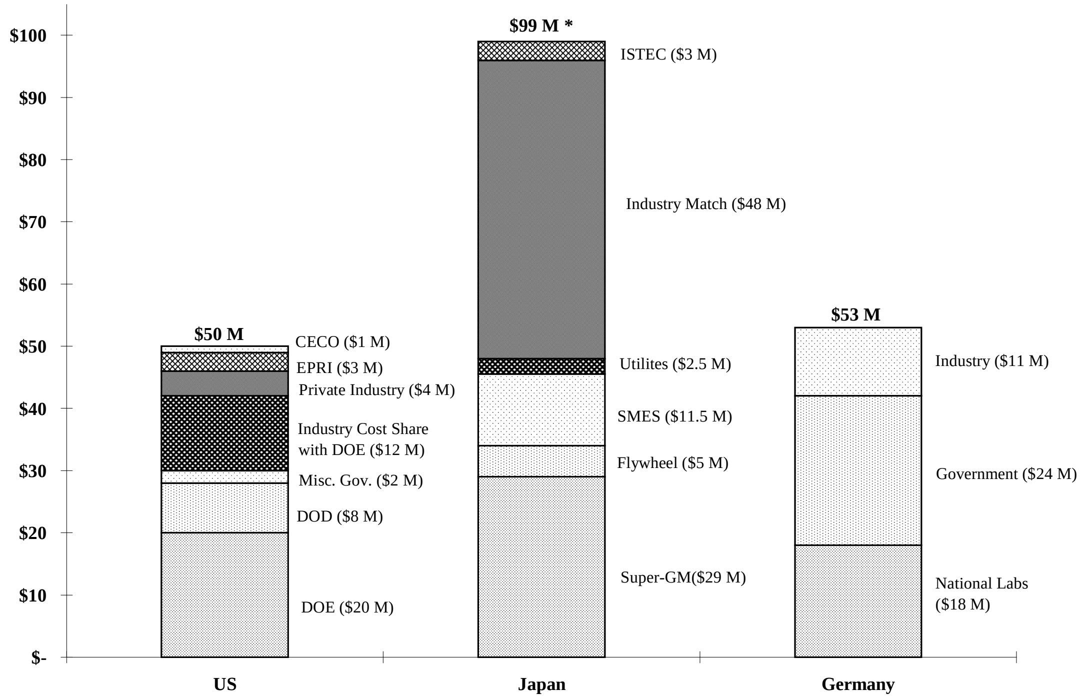
Table ES.1
U.S. Competitiveness in Power Applications of Superconducting Materials
High T_c Wire Technology

U.S. Standing	**Compared to Japan**		**Compared to Germany**	
	Status	Trend	Status	Trend
Lagging	Bi-2212 wires	Bi-2212		
Holding	Bi-2223 wires Y-123 on metallic substrates Tl tapes	Bi-2223 tapes Tl-1223	Y-123 tapes	
Leading		Y-123 tapes	Bi-2223 Bi-2212 Tl-1223	Y-123 tapes Bi-2223 Bi-2212

Table ES.2
U.S. Competitiveness in Power Applications of Superconducting Materials
Systems Technology

U.S. Standing	**Compared to Japan**		**Compared to Germany**	
	Status	Trend	Status	Trend
Lagging	Generators Maglev Fault-current limiters	Generators Maglev Flywheels	Transformers (ABB)	
Holding	Current leads Power cables Transformers Flywheels	Fault-current limiters Power cables Current leads	Flywheels	Fault-current limiters Transformers Flywheels Current leads
Leading	Motors SMES	Motors SMES Transformers	Power cables Current leads SMES Fault-current limiters Motors	Power cables Motors SMES

The Germans appear to share the Japanese view that LTS programs are very important at this stage of power applications development. Germany has strong programs going back 25 years that are committed to large-scale applications of superconductivity, particularly for fusion applications. Fusion magnets are several meters in diameter and are complex devices requiring large and sophisticated refrigeration systems. The national laboratories supporting this effort (these labs are mainly supported by Germany's Ministry of Education, Science, Research, and Technology, BMBF) provide excellent continuity and a base for large multinational Germany-based companies, especially Siemens. The BMBF program in power applications has now run for four years, and there is a strong expectation that a new four-year program is imminent. The BMBF appears quite firm in its position that HTS work for power applications is both promising and precompetitive. The BMBF program also appears to be strongly interactive: for example the BSCCO conductor program involves extensive collaboration between Siemens, Vacuumschmelze, Forschungszentrum Karlsruhe, and the IFW-Dresden. The biaxially textured YBCO program, which is industry-led, also features important contributions from universities and national laboratories.



*Does not include Maglev ($3.5 billion over 5 years), a large percentage of which is for land acquisition and construction. Note also that U.S. dollar equivalent amounts for the Japanese program were calculated using 1996 exchange rates (¥100/$), which have fluctuated considerably since then.

Fig. ES.1. R&D related to power applications of superconductivity: 1996 funding profiles of the United States, Japan, and Germany.

U.S. activities are highly leveraged from the program of the Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE). Small start-up companies play a major role, and collaborations have been vital to the rapid progress that has occurred in the United States. Demonstration devices using HTS are more widespread in the United States than in either Japan or Germany. The schedule for further scale-up is ambitious, but the actual implementation appears to depend strongly on a healthy federal- and utility-funded program.

Trends in the relative standings of the United States, Japan, and Europe in the field of conductor technologies do not appear to differ greatly from the present situation: assuming a continued commitment to coated conductors, panelists anticipate that the U.S. program in YBCO tapes will lead both Japan and Germany.

In the area of superconducting systems technology (Fig. ES.2), the panel estimates that the United States is lagging Japan in generators, magnetic levitation, and fault-current limiters, and is lagging Europe (specifically, ABB Group) in transformers. The WTEC panelists believe that U.S. systems technology is level with Japan with respect to current leads, power cables, transformers, and flywheels, and is leading Japan and Germany with respect to motors and superconducting magnetic energy storage (SMES). The United States is also leading Germany in the areas of power cables, current leads, and fault-current limiters.

Changes in the relative standings of the United States, Japan, and Europe with respect to systems technologies are more likely than with respect to wire technologies. Present U.S. interest in both fault-current limiters and transformers gives a boost to the U.S. position in both areas and suggests that U.S. transformers might eventually take the lead with respect to Japan and reach parity with comparable German developments. This would give the United States a leading position in transformers, motors, and SMES compared to Japan, and a leading position in power cables, motors, and SMES compared to Germany.

The uncertainty of these estimates is addressed in detail in the individual chapters on each component of the power system. The panelists were unanimous in the view that the future position of the U.S. program depends vitally on a strong federal program, since this underpins all of the advances on which the judgments in Tables ES.1 and ES.2 depend. A point that Japanese hosts made to the panelists several times concerns the importance of a strong U.S. program even to the Japanese, although their program was about twice the size of the U.S. program in 1996.

The funding data shown in Figure ES.1 should be viewed with some caution. Because of the diverse nature of the funding mixes that support work in the different countries, the particular uncertainties about industrial contributions, and extent to which contributions to one aspect of superconductivity work carry over to another, it is not easy to accurately count all components of each national program on power applications of superconductivity. Note also that Figure ES.1 does not reflect the budget increase in the DOE program recently approved for FY 1998 ($32.5 million, vs. $20 million in FY 1996).

IMPLICATIONS FOR THE U.S. PROGRAM

The goal of the U.S. program is to be first to market power applications of HTS materials. All three countries have this goal, but the Japanese and German view is that significant markets for HTS power applications will take a decade or more to develop. There is a dichotomy of view in this debate that not only encompasses national perceptions but is also associated with the contrast between small-company views (dominant in the United States) versus large-company views (dominant in Japan and Germany). Large companies appear to be more comfortable with working on demonstrations of HTS technology, which might be far from being economic in the near term, provided they are part of a technology-enabling path. Small companies must come to market sooner and thus are looking for more immediate applications, many of which might be economic on a smaller scale. HTS can enter the global marketplace, perhaps bringing superconducting devices to less developed economies that lack the resources to implement the expensive and complex liquid helium (LTS) technologies. Due to the multinational nature of large companies, they are certain to play a large role in bringing superconductivity to market, but it is the small, venture-capital-supported companies that are playing the most vital role in the present U.S. effort.

Because of the dominant role played by smaller companies in the US program, the partnership aspects of the U.S. program, which bring together government, small companies, the stock market, large companies, universities, and national laboratories at the same table, are vital (see Chapter 1). Most technology is still at the precompetitive stage, making continued innovation vital. In Japan and Germany this is clearly recognized as being the case. In spite of the small markets that do now exist, large global markets for power applications of superconductivity have not yet developed, and governments are playing a continuing and important role in funding all programs, whether in the United States, Germany or Japan.

A characteristic of U.S. work has been the development of really outstanding interinstitutional collaboration. There has been a concern that this could be lost in the dynamic budget process that characterizes U.S. government funding of the field; however, for the time being the DOE budget for this program has fared well in Congress, with a substantial increase recently approved for FY 1998. This increase seems well justified since the current U.S. program has been extremely successful with only limited funds. It has generated strong demonstration devices and supported an R&D community that is responsible for many recent successes in conductors based both on BSCCO and on biaxially textured YBCO.

FUTURE MARKETS

The future for power applications of superconductors has many aspects. Synthesizing the views of all the WTEC panelists, superconductor power applications are immediate as well as long term. Applications that are going to market today are HTS current leads, which couple external power supplies to LTS magnets much more effectively than the copper/LTS leads used up to now. Such leads enable so called “cryogen-free” ("dry") magnets. Toshiba, Mitsubishi Electric, and Kobe Steel/Japan Magnet Technology have been effective at this, as has the British company Oxford Instruments. Also, two U.S. companies are shipping SMES units for power quality purposes.

Dry magnets could be very important to the world market of even LTS magnets, since they remove the need for the complex infrastructure required to supply liquid helium. Dry magnet technologies can make powerful magnets available in the United States, Japan, and Germany not just for physics research but for new applications where no expertise in handling liquid helium exists. Professor Kitazawa of Tokyo University told the WTEC panel that one of the new initiatives of Japan's Science and Technology Agency program was to buy dry magnets and put them into Japanese research institutes that have no prior experience with strong magnetic fields. Such markets are being exploited now.

Next to be exploited will be larger SMES units, which give some spinning reserve and protection against large disturbances to the electricity supply. Next to be exploited after that will be superconducting transmission lines, of which excellent prototypes exist in Japan and the United States. Fault-current limiters, motors, energy storage flywheels, and transformers are all being worked on now. A strong complication in the United States that does not occur in either Japan or Germany is that the U.S. electric utility industry is contending with several years of deregulation and much competition. This is quite different from the relative stability of the Japanese and German electric utility industries.

OUTLINE OF THE REPORT

Chapter 1, by David Larbalestier, explains the study background, objectives, and methodology, then reviews the accomplishments of the U.S. program and makes some general observations on and comparisons between the Japanese and German programs. Chapter 2, by Richard Blaugher, includes extensive background discussion on the history of superconductivity and its power applications, and reviews generation and storage applications. Chapter 3, by Robert Sokolowski, reviews transmission and distribution applications. Chapter 4, by Robert Schwall, covers other applications (i.e., flywheels, fault-current limiters, HTS leads and high field magnets, and cryocooling). Chapter 5, by Jeffrey Willis, gives an overview of HTS conductor technology. Chapter 6, by Masaki Suenaga, reviews the extensive Japanese R&D program in low T_C conductors and applications. Biographies of the WTEC team members and site reports on each of the team's visits in Japan and Germany are included as appendices, along with a partial list of World Wide Web sites for the organizations visited abroad and a glossary of technical terms used throughout the report.

CHAPTER 1

INTRODUCTION

David Larbalestier

THE VISION OF A NEW 21ST CENTURY TECHNOLOGY: POWER APPLICATIONS OF SUPERCONDUCTIVITY

In early 1986, Bednorz and Mueller (1986) made the amazing and unexpected discovery of high temperature superconductivity (HTS) in an entirely new class of layered-perovskite, oxygen-sensitive, copper-oxide ceramics. The new material, $(La,Ba)_2CaCu_4O_{4-x}$, had a superconducting transition temperature (T_c) of about 35 K, 50% greater than the best existing low temperature superconductor (LTS) of the time, Nb_3Ge, whose T_c is 23 K. This discovery underlies this entire World Technology Evaluation Center (WTEC) study. To exemplify the impact of the discovery, it should be noted that all superconducting technology of the time was based on the use of just two materials, Nb 47 wt.% Ti and Nb_3Sn, having T_c values of 9 and 18 K, respectively; thus, their application was directly tied to liquid helium technology, for which the operating temperature range is approximately 2-6 K.

To dramatize the unexpected discovery of HTS, 1986 was also the 75th anniversary of the discovery of superconductivity. The science of superconductivity was doing rather well in 1986. It was 25 years since the 1961 discovery that Nb_3Sn could support high critical current density (J_c) at magnetic fields of almost 9 tesla. This 1961 discovery enabled the construction of strong magnetic fields for many purposes. Among these were many types of laboratory magnets, large particle accelerators, and the first truly civilian application of superconductivity, magnetic resonance imaging (MRI). Equally germane for the present WTEC study was the fact that by 1986, the technical feasibility of making many of the components of a power transmission system — generator, motor, and power cables — had all been demonstrated using Nb 47 wt.% Ti or Nb_3Sn. Economic feasibility was a different issue: For some applications like MRI, particle accelerators, and laboratory magnets, there was no disadvantage to operation at 4-5 K using liquid helium technology, but for others, the commercial outlook was bleak due to the cost and technical obstacles associated with operation at liquid helium temperatures. Nevertheless, the superconductor industry was on a steady growth curve, and on the 75th anniversary there was optimism about the future in the field of superconductivity. This anniversary was celebrated in several ways: *Physics Today* had a special issue in March 1986 devoted to superconductivity (Tinkham 1986), and the September 1986 Applied Superconductivity Conference had a retrospective honoring the history of the field, paying special attention to the applications (Edelsack 1987). It is ironic that the most concrete prediction of higher T_c was for the compound Nb_3Si, whose T_c might possibly reach 30 K (Hughes 1986); unknown to almost all was the submission of the paper on $(La,Ba)_2CaCu_4O_{4-x}$ that would soon lead to new compounds having T_c greater than 100 K.

By March of 1987, the news that Wu, Chu, and others (Wu 1987) had succeeded in discovering a new member of the class $YBa_2Cu_3O_{7-\delta}$ had spread around the world, reaching *Fortune*, *Time*, *Newsweek*, and Japanese comics, to name a very small part of the new public for superconductivity. From this arose a vision of a new superconducting age: where copper or aluminum had been, superconductors would now take over. Superconducting generators would produce electricity, superconducting cables would transmit it, superconducting motors would put the power to use, and superconducting magnetic energy storage units would manage the power quality (Fig. 1.1). Thus, all of the promises demonstrated by LTS devices might actually come to fruition very quickly. The sense of a new age dawning was enhanced by the belief that room temperature superconductivity was just around the corner. Hopes at this time were unconstrained, even by many in the scientific community, for the mechanism of superconductivity in these new compounds was not at all understood. What was clear was that the electron-phonon coupling mechanism responsible for *low* temperature superconductivity was not capable of giving superconductivity at 100 K, let alone room temperature. The possibilities for high temperature superconductivity seemed limitless.

A decade later, what has become of these dreams? It is clear that a decade is a very short time indeed in which to market basic scientific discoveries, even those such as semiconductors that now exert a massive presence in daily life. The transistor was invented in 1948, but it was the late 1950s before commercial transistors began to enter the electronics market, and the full flowering took another 10-15 years. Today, 10, not 25, years on, superconductors are available with transition temperatures well above liquid nitrogen temperature (77 K) with T_c up to 135 K. Some HTS materials can be made into useful conductors, permitting engineering-scale prototype electrical machines to be demonstrated; however, applications are still dependent on attainment of greater scientific understanding of these very complex materials. Nevertheless, a talented and committed community of researchers, engineers, entrepreneurs, and industrial and government visionaries is working hard throughout the world to bring the vision of the superconducting power economy to fruition. The WTEC panel came back from trips to Japan and Germany convinced that this new economy is a viable 21st century possibility. This report details the basis for this conclusion.

Fig. 1.1. Superconductivity in the electric power system of the future, with widespread use of superconducting generators and motors, fault-current limiters, underground transmission cables, and superconducting magnetic energy storage (Blaugher 1995).

THE WTEC PANEL

The aim of the WTEC panel was to assess, relative to the United States, how Japan and Germany have responded to the challenge of applying high temperature superconductivity to power and energy applications. Although the primary motivation for the study came from the desire to assess the impact of high temperature superconductors on the power applications field, the panel also found wide agreement that there are still many applications for low temperature superconductors. The market for low temperature superconductor applications is well established, as is that for superconducting electronics, for which there is a separate WTEC panel. The WTEC panel on power applications of HTS was commissioned to identify the roles and responsibilities of public organizations, industry, and academia for advancing power applications of superconductivity. The panel was asked to take both a present and a long-term view.

The panel performed within the usual broadly representative framework of WTEC studies, having one academic, four national laboratory, and three industry members. Because of the exigencies of time and budget, panelists could only visit representative centers in Japan and Germany, which, with the United States, have the three largest programs worldwide. However, HTS studies now exist throughout the world, and the panel also made a side trip to Switzerland to visit a significant program there. Eight panelists went to Japan, where they visited 18 sites; two panelists then went on to Germany and Switzerland, where they visited 5 sites; thus, there was an imbalance in the effort applied to studying Japanese and European programs.

The traveling team consisted of Richard Blaugher (Superconductivity Technology Manager of the Department of Energy program at the National Renewable Energy Laboratory in Golden, CO); Paul Grant (Executive Scientist at the Electric Power Research Institute); Donald Gubser (Superintendent of the Materials Division in the Naval Research Laboratory in Washington, DC); Robert Schwall (Vice President, American Superconductor Corporation in Westborough, MA); Robert Sokolowski (Vice President and General Manager, IGC Advanced Superconductors in Waterbury, CT); Masaki Suenaga (Senior Scientist, Brookhaven National Laboratory in Upton, NY); Jeffrey Willis (Technical Staff Member, Los Alamos National Laboratory in NM), and David Larbalestier (Panel Chair, Professor, and Director of the Applied Superconductivity Center, University of Wisconsin, Madison, WI). The expertise of panel members was well distributed between the materials aspects, the conductor aspects, and the device aspects of HTS.

SITE VISITS IN JAPAN AND EUROPE

In Japan the panel divided up into two teams. All panelists went to the New Energy and Industrial Technology Development Organization (NEDO) of the Ministry of International Trade and Industry (MITI). Team A then went to the Nikko works of the Furukawa Electric Company, where superconductors are manufactured, and which is also Furukawa’s principal copper- and aluminum-manufacturing facility. Furukawa is known as one of Japan’s leading superconducting wire manufacturers, making both LTS and HTS wire. On the second day Team A went to the Superconductivity Research Laboratory (SRL) of the International Superconductivity Technology Center (ISTEC) in Tokyo and to Toshiba’s Keihin works in Kawasaki. This is Toshiba’s large electrical machine manufacturing works, where the superconducting rotor for the Super-GM generator and other large devices are made. On the third day this team went to the Yamanashi Maglev test site. On the fourth day it went in the morning to the Kobe Steel Research Laboratory, where Japan Magnet Technology and its MRI magnetic fabrication facility is located, and in the afternoon to Sumitomo Electric Industries Company (SEI) in Osaka. On the fifth day Team A visited the Fujikura Research Laboratory in Tokyo and the laboratories of Professor Kitazawa at Tokyo University.

Team B also started at NEDO, then went to the Hitachi Research Laboratory in Hitachi City. On the second day it visited the National Research Institute for Metals (NRIM) and the High Energy Physics Laboratory (KEK). On the third day it went to Tokai University and to Tokyo Electric Power Company (TEPCO). On the fourth day this team went to the Super-GM site of the generator program in Osaka and to Mitsubishi Electric Company (MELCO). On the fifth and final day it went to Chubu Electric Power Company and to the Central Research Institute for the Electric Power Industry (CRIEPI).

In Germany, Blaugher and Larbalestier went to Cologne to participate in the Statusseminar (a review of the German Federal Ministry for Technology [BMBF] program in applied superconductivity), the first day of which was devoted to power applications. They then went to Vacuumschmelze on the second day, and to the central Siemens research laboratory in Erlangen on the third. On the fourth day they visited the ABB Research Laboratory in Baden, Switzerland, and returned to Germany on the fifth day for a visit to the Institute for Technical Physics and the Institute for Applied Superconductivity in Forschungszentrum Karlsruhe (FZK).

The panel's findings are presented in detail in the separate chapters on power systems, generation, and storage (Chapter 2); power transmission and distribution (Chapter 3); high field magnets and other power applications (Chapter 4); conductor technology (Chapter 5); and the current status of low T_c R&D in Japan (Chapter 6). Here follows a brief summary of the findings.

THE U.S. PROGRAM

In the United States the program to develop power applications of superconductivity is led by the Department of Energy Office of Energy Efficiency and Renewable Energy (DOE EERE), which has by far the largest U.S. program. It gains some support from the Electric Power Research Institute (EPRI) program and programs in the Defense Advanced Research Projects Agency (DARPA) and the Navy. The U.S. program has historically been large, but the uncertainties of the present program are considerable. This uncertainty is a major concern at present, since the technology is in the midst of a major thrust to address real utility applications.

There are two very well defined parallel thrusts in the U.S. program. The first focuses on development of HTS conductors. This thrust is based on a firm belief, which panelists found during our visits to be entirely shared by the Japanese and European research community, that the conductor is the critical element for the whole of HTS technology. However, conductors need devices to justify tackling the manifold problems of scaling up for production, and developing devices is the second thrust. Thus, a parallel program emphasizing both conductors and devices can develop effective and rapid feedback for the technology. These same two parallel thrusts characterize the U.S., Japanese, German, and Swiss programs.

A significant characteristic of the U.S. program is that it is more aggressively focused on early device demonstrations than that in either Germany or Japan. In both of those countries there is a greater sense that superconductivity is bound to be an important 21st century technology and that today's work can proceed in a measured and confident way. By contrast, the U.S. program is hustling along, trying to make HTS applications occur in the 20th century. A significant component of this effort has been an extremely effective linkage between the U.S. industry, national laboratories, and universities. This has been remarked upon specifically by members of Japanese study missions to the United States.

The DOE EERE program serves as the primary benchmark against which to compare the German and Japanese programs. The principal element of the DOE EERE program strategy is that there are both wire and systems technology components. Twenty-three companies, six national laboratories, and ten universities collaborate on the wire component within a legal framework that provides for intellectual property protections. The systems part of the program is carried out through the Superconductivity Partnership Initiative (SPI). This involves four industry-led teams, each of which is committed to substantial cost-sharing and to commercialization of the technology on which they are working.

Even a brief review of this program is impressive, considering that it was only in 1990 that the prospect of a reasonable conductor made from an HTS material was first demonstrated. Demonstration devices of real significance have come remarkably quickly in these past seven years, including a 200 horsepower industrial motor (Fig. 1.2), a 50 m, 1,800 ampere power cable, and a 2.4 kV fault-current limiter. These units have all been based on HTS conductors made from the $(Bi,Pb)_2Sr_2Ca_2Cu_3O_x$ (BSCCO-2223) compound. Conductors made from BSCCO have been advancing very strongly since 1995, and these advances are not yet fully incorporated into the devices. Even more promising for conductor technology is that 1995-1996 brought genuine possibilities of second-generation conductors based on biaxially textured $YBa_2Cu_3O_{7-\delta}$ (YBCO).

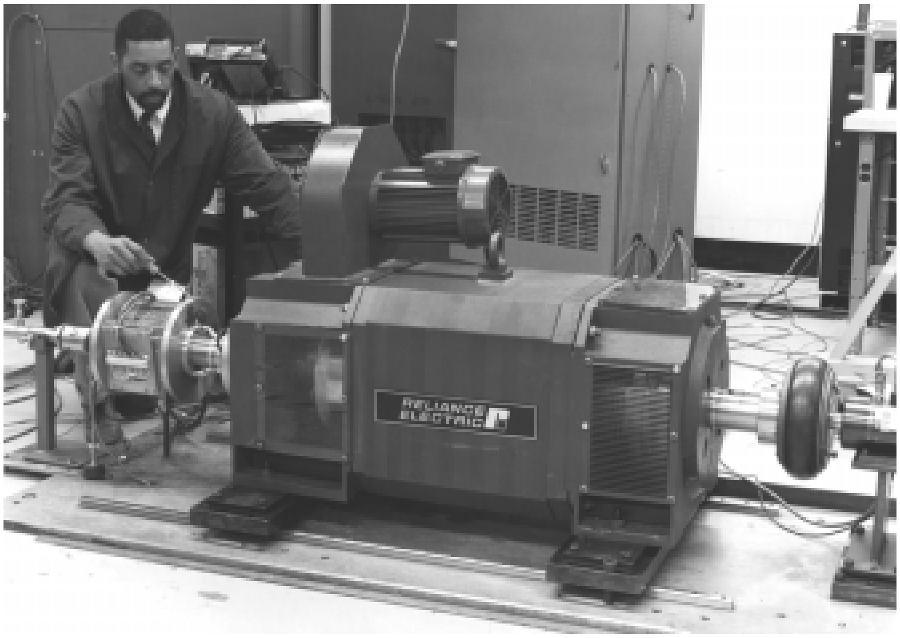


Fig. 1.2. World-record 200 hp HTS motor tested by Reliance/DOE team in early 1996.

These developments use a technique first developed in Japan by Fujikura but since developed further in important ways by Los Alamos and Oak Ridge National Laboratories (LANL, ORNL). Table 1.1 summarizes the program and its thrusts and successes since its inception in 1990.

Table 1.1
Achievements of the DOE Power Applications Program

	1990	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**
Wire Development							
-Silver tube	10 m		100 m		1 km		
-Film						Over 1,000,000 amps/cm^2 (LANL)	New ORNL process
Coil Development	0.1 tesla			2.5 tesla		3 tesla	
Superefficient Systems Projects							
-Motors				Start➔			200 hp
-Power Cables							
-Pirelli/EPRI				Start➔	4,200 amps		50 m
-Southwire						Start➔	
-Generators				Start➔			34 amp coil
-Transformers						Start➔	
-Current limiter				Start➔		2.4 kV prototype	

THE JAPANESE PROGRAM

A vital characteristic of the Japanese program is a belief in the importance of advanced technologies and new materials, of which the high temperature superconductors are certainly part. There is a widespread belief that superconductivity is going to be a vital 21st century technology, not just in the power applications field but also in electronics. The Japanese program in applications of superconductivity dates from 1962, when high field superconductivity first became a possibility. The program has continued, even through the recession that has hit Japanese industry so hard. Panelists were told time and again that the commitment to superconductivity will continue, because there does not have to be a payback in two or three years. Unlike the situation in the United States, there is a distinctly large-company focus to superconductivity work in Japan, and there is a greater tendency to integrate low and high temperature superconductivity. This can be seen in the Super-GM program, which uses LTS rotors for the 70 MW-class generators but which also supports development of a wide range of LTS and HTS conductors aimed at use in transformers, fault-current limiters, and other devices.

THE GERMAN PROGRAM

The German program appears to be more focused than either the U.S. or the Japanese programs. The BMBF plays a dominant role in funding the applied programs in superconductivity, but details of the program are worked out with the large German utilities. There is a particularly strong fusion program at the Forschungszentrum Karlsruhe, which supports large capabilities in helium cryogenics and LTS high field magnets. As in Japan, this large LTS expertise leads to a greater willingness to try out devices based on LTS conductors, even if real economical applications would come only from HTS conductor use. This strong LTS base is a very important component of the German program. The BMBF program requires cost-sharing by industry of about 50%, thus making the German program now about the same size as the U.S. program (Figure ES.1, p. xi). The German program on power applications has greatly strengthened in the last two years. As in Japan, it is sustained by a basic belief that superconductivity will be a key 21st century technology.

REFERENCES

Bednorz, J.G., and K.A. Muller. 1986. *Z. Physik* B64: 189.

Blaugher, R. 1995. In *Advances in Cryogenic Engineering* 42. New York: Plenum Press.

Dew Hughes, D. 1986. *Cryogenics* 36: 660.

Edelsack (Conference Chair). 1987. *IEEE Trans. on Magnetics*, Applied Superconductivity Conf., Sept. 1996. Mag 23(2): 354-1841.

Tinkham, M. 1986. Superconductivity, 75th anniversary. *Physics Today* 39: 22.

Wu, M.K., et al. 1987. *Phys. Rev. Lett.* 58: 908.

CHAPTER 2

POWER SYSTEMS, GENERATION, AND STORAGE

R. D. Blaugher

INTRODUCTION

The interest in applying superconductivity (SC) to electric power and energy storage applications is directly related to expectations for improved performance and efficiency advantages over conventional room-temperature devices. Use of superconducting wire or tape in power generators or large magnets, for example, provides the ability to transport large dc currents with no measurable resistive losses. High magnetic fields can thus be produced at a significantly reduced cost for the energy required for operation. This economic advantage is also driven by a simple caveat that the superconductor should provide the ability to generate sufficient amp-turns within a specific volume. A practical superconductor must thus have a current density, at high magnetic fields, in excess of ordinary copper in order to be technologically useful. The early so-called "low temperature" superconductors (LTS) that operated in liquid helium easily satisfied this requirement and as a result spurred the development of many prototypes for generators, motors, transmission lines, and energy storage magnets. All of these demonstrations were compromised by the costly and technologically complicated requirement for liquid helium; consequently, they were not easily accepted by utilities or end-users, especially in the United States.

The 1986 discovery of high temperature superconductors (HTS) excited the scientific community and provided new impetus for pursuing superconducting electric power applications because of the prospect for higher temperature operation at liquid nitrogen (77 K) temperatures or above. It is fair to say that this HTS discovery would have been of little importance if the earlier work of Shubnikov and Abrikosov in the Soviet Union had not recognized that certain superconducting alloys identified as Type II superconductors had the ability to carry high transport currents in technologically useful magnetic fields (Larbalestier 1990, 1027).

It was eventually determined that highly cold-worked alloys, such as Nb-Ti and Nb-Zr, contain a wide range of defects, impurities, and precipitates that act as "pinning centers" limiting the movement of flux, which results in a highly hysteretic magnetization and the ability to carry high transport currents at high magnetic fields. These materials with high pinning and outstanding transport properties, referred to as "hard" superconductors or "dirty" Type II materials, have been rapidly developed to provide fairly cost-effective wires or tapes with acceptable mechanical properties (Berlincourt 1987).

EARLY HIGH FIELD MAGNETS AND ENERGY STORAGE

In 1961, Kunzler et al. prepared the first practical powder-in-tube conductor by drawing a Nb tube filled with Nb_3Sn powder into a wire. Following reaction, the wire showed very high critical current density of

~10^5 A/cm^2 at magnetic fields up to 8.8 T (Kunzler et al. 1961). This result provided the first real demonstration of high field superconductivity and at that time produced as much excitement for superconductivity as seen in the subsequent HTS discovery. Kunzler and his coworkers eventually wound the Nb_3Sn wire into a solenoid, which produced a field of 7 T (Kunzler 1987).

Kunzler's experiment thus opened the "Type II" superconductor era, offering enormous potential for superconducting magnets and electric power applications. Shortly after Kunzler's work was reported, Hulm and Blaugher (1961) published their studies on the Group IV, V, and VI transition metal alloys, four of which included the body-centered-cubic Nb-Ti and Nb-Zr systems. The Nb-Ti alloys were eventually shown to be the most technologically important because researchers were able to inexpensively fabricate long lengths of conductor with high current properties in useful magnetic fields of 3 to 5 T. Within a year, these hard superconducting Nb-Ti and Nb-Zr alloys were fabricated into wires and wound into solenoids, producing magnetic fields up to 7 T. The successful test of these solenoids quickly established that the transition alloy conductors could be easily applied to a wide range of electric power-related applications.

The idea of using large SC magnets for energy storage follows directly from the expression describing the energy stored in an inductor, which is simply, $E(J) = ½LI^2$, where L is in henrys (H) and I, the current, is in amps. Following the demonstration of high field magnets in the early 1960s, magnetic energy storage was immediately considered, but advances in fabricating a high-current cabled conductor were necessary before serious programs could be pursued. The major programs on superconducting magnetic energy storage (SMES) started in the early 1970s and continued through the mid-1980s. The primary interest for these magnets was directed at diurnal storage for load leveling and the need for a pulsed power source for current induction in the plasma of Tokamak fusion power devices. The SMES effort during this period, which was concentrated in the United States and Japan, is reviewed by John Rogers (1981).

The energy storage effort in Japan from the 1970s to the 1980s was fairly widespread, with most of the major electric power companies such as Hitachi, Mitsubishi, and Toshiba participating. In addition, storage programs were pursued by some of the utilities, in particular, by Chubu Electric Power and Kansai Electric Power companies. Hitachi built and tested a 5 MJ SMES system in 1986, which was connected to the 6.6 kV power line of the Hitachi Works to evaluate transmission line stability (Ishigaki, Shirahama, and Kuroda n.d.). In 1989, Chubu Electric and Hitachi jointly studied and developed a 1 MJ SMES system to evaluate how a SMES could provide power system stability (Fujita 1989). It is important to note that a "SMES system" includes the SC magnet, a fairly sophisticated solid state ac-dc power conditioning system (PCS), and usually a closed-cycle refrigerator. The SMES system is also interfaced with additional circuit breakers and a control system for protection and isolation. The response time for the SMES is thus dependent on the PCS and associated switch gear, which is fairly fast, allowing a SMES system to demonstrate high-speed response with capability of the order of one cycle or approximately 10 ms.

The major achievement in the United States during this period was the construction and successful test on the Bonneville Power System of a 30 MJ SMES to damp low frequency oscillations between two ac transmission lines running from the Pacific Northwest to Southern California (Rogers et al. 1985).

SUPERCONDUCTING ELECTRIC POWER APPLICATIONS

The early activity to demonstrate high field superconducting magnets, which achieved field levels greater than 10 T in a relatively short period, was essentially paralleled by a comparable effort toward applying these Type II superconductors to a wide range of electric power applications. The superconducting power applications can be divided into two categories:

1. high field > 1 T applications — generators, motors, fusion, magnetohydrodynamics (MHD), energy storage
2. low field < 1 T applications — transmission cables, transformers, fault current limiters (FCL)

The distribution-level FCLs are, for the most part, low field designs, < 1 T, with some of the subtransmission- and transmission-level FCL concepts in the > 1 T range. Some of the low field applications, such as transformers and transmission cables, expose the superconductor to a high level of ac line conditions since they are directly inserted into the ac system; they thus require a conductor design that shows an acceptable ac loss. Some of the FCL designs also expose the superconductor to a high ac field component and therefore need a low-ac-loss conductor. As a result of conductor limitations, work on most "full ac" applications was deferred until the 1980s, when the theory and an ac conductor were more sufficiently developed. The ac transmission cable is an exception as a result of the very low fields of $H_{op} < 0.1$ T and the ability to use available Nb_3Sn tape conductor, which allows the major field component to be parallel to the plane of the tape. Table 2.1 highlights some of the major electric power components that were constructed and successfully tested during the 1970s and 1980s using liquid helium LTS technology. It is clear from this table and the references it cites that the major world efforts were concentrated in the United States and Japan.

Table 2.1
Highlights For Superconducting Electric Power Components
Constructed and Tested from 1970-1990 Using Low Temperature Superconductors

Application	Highlight (Rating And Group)	Reference
AC generators	20 MVA, GE; 50 MVA, Hitachi; 12,000 rpm, Westinghouse/USAF; 300 MVA, USSR	Smith et al. 1975; Fujino 1983; Smith 1983; Laskaris and Schoch 1980; Glebov and Shaktarin 1983; Blaugher et al. 1974; Edmonds 1979
Motors (homopolar)	3,250 hp, IRD England; 1,000 hp U.S. Navy	Smith et al. 1975; Appleton 1975
AC transmission	1,000 MVA, 138/80 kV, BNL	Forsyth and Morgan 1983
Magnetic energy storage	30 MJ, LANL-Bonneville Power	Rogers 1981; Rogers et al. 1985
Current limiters	~ 2 MVA, 3 kV, IRD England	Raju and Bertram 1982
Transformers	72 kVA, Kyushu Univ.	Funaki et al. 1988
Magnetohydrodynamics (MHD)	6 T, ANL-CFTF Tullahoma	Wang et al. 1981

Superconducting Synchronous Machines

One of the first high field superconducting power applications considered, which this author believes to one of the most important, was to apply high-current-density superconducting wires to electric power synchronous generators. The following discussion on ac synchronous generators also applies to ac synchronous motors, which use an identical design approach, as discussed later for the Reliance Electric motor program. The early machine activity on motors, however, was primarily directed at the dc homopolar design, which allows the use of a "stationary" dc superconducting solenoid (Smith, Kirtley, and Thullen 1975; Appleton 1975). The later activity was concentrated in the United States under U.S. Navy sponsorship and in England.

The basic principal for all rotating electric machines is associated with Faraday's law, which describes the electromagnetic energy conversion related to mechanical movement. In a rotating machine, time-varying voltages are produced in an interconnected set of coils called the "armature winding," which is mechanically moved through a magnetic field, or a magnetic field is mechanically moved past the winding. This magnetic field is produced by the excitation coils or "field winding," which is essentially a dipole magnet for a 2-pole design. If the armature is stationary, it is referred to as the "stator"; the rotating field winding is the "rotor."

It is important to note that the early rationale for SC ac machines primarily emphasized the use of superconductors to achieve higher current densities, which allowed an overall reduction in cross-section and field winding volume compared to ordinary copper-wound rotors. The reduced winding volume thus led to a reduction in the size and weight of the entire machine. The preferred design approach for an ac SC machine developed and demonstrated during the 1970s was to use a stationary room-temperature armature with a rotating SC field winding, which posed difficult problems concerning transferring cryogen into a rotating vacuum-insulated container (Edmonds 1979, 673).

In a synchronous machine, alternating current is supplied to the armature to provide a flux component that rotates in synchronism with the flux component produced by the rotating field winding. The rotor is thus phase-locked at the synchronous speed and under balanced load conditions will see essentially a dc field from the armature. The armature, however, is connected to the electric power system, which experiences load-related electrical disturbances under steady state and transient conditions. These electrical disturbances are reflected back into the armature and produce nonsynchronous ac effects that impact the rotor. Rapid changes in the dc excitation (field forcing) also occur as a result of load changes. The primary armature disturbance is caused by unbalanced loads, which gives rise to negative sequence currents, proportional to the load and degree of unbalance, that counter-rotate at twice the synchronous speed.

Transient events caused by system faults provide the other major source for nonsynchronous ac effects on the rotor. These time-varying fields in the armature, at frequencies different from the synchronous frequency, induce compensating currents to flow in the rotor and produce heating in the dc superconducting winding and structural support. This ac influence, however, can effectively be minimized by incorporating warm and/or cold electromagnetic shields between the two windings that attenuate these nonsynchronous ac fields. The warm shield also provides damping for the mechanical oscillations of the rotor related to the phase of the system. Because the thermal margin for LTS conductors, assuming liquid helium cooling, is between 6 K for Nb-Ti and 14 K for Nb_3Sn, the shielding must be carefully designed to minimize ac heating of the field winding and to prevent degradation of the superconductor J_c and magnetic field capability and possible normalization during extreme transient conditions.

Following the first demonstration of an ac synchronous machine with a rotating SC field winding in 1971, major research programs were initiated in the United States, Europe, Japan, and the USSR — the United States and Japan being the major players (Thullen et al. 1971). During the 1970s, a number of machines were built and successfully tested, highlighted in Table 2.1, that completely demonstrated that ac superconducting machines could be built in large sizes suitable for electric utility installation. The 12,000 rpm SC four-pole rotor test by Westinghouse for the United States Air Force (USAF) Wright-Patterson Laboratories, demonstrated, due to the high centrifugal loads on the superconducting winding, that larger machine diameters with ratings near 1,000 MVA could be successfully constructed and operated with liquid helium (Parker et al. 1975).

The principal arguments advanced during this period were that ac superconducting machine technology could achieve (1) efficiency improvements near 1%, (2) decreased size and weight for equivalent ratings, (3) ability to manufacture larger size generators than is possible with conventional technology, (4) improved steady state and transient system performance, and (5) reduced life-cycle costs, assuming reliability and maintenance comparable to existing units.

The prospect of approximately 1% increased efficiency for the SC machine offered to the utilities substantial savings in annual operating costs as a result of reduced fuel consumption. The savings in fuel costs were, in fact, so large over the ~40-year lifetime of conventional machines that they could almost completely offset the initial cost of the generator. This savings, however, was completely dependent on the SC generator having a reliability profile identical to that of a conventional unit. Furthermore, if the SC generator experienced even one additional day of outage per year compared to a conventional unit, the efficiency-derived savings would be essentially eliminated. The reliability and maintenance profile for an SC generator must therefore be identical with a conventional machine to ensure its economic benefit. Because it would take many years to produce sufficient operating experience to obtain an acceptable reliability profile, the utilities adopted a reserved attitude towards the projected savings resulting from improved efficiency.

SC ac machine technology, however, in addition to efficiency improvement, offered an impressive list of system improvements that caught the interest of and excited utility customers. Studies by the Japanese under their Super-GM program have confirmed and cited these system improvements as a major driver for the eventual commercialization of superconducting generators (Ogawa 1992).

To summarize the commercial interest in developing superconducting generators, technical interest was originally driven by the ability of SC generators to increase current density, which permitted higher magnetic fields and allowed a reduction in weight and size. In addition, the technology made possible the realization of increased machine efficiency because of the elimination of I^2R heating in the field winding, which quickly became the focal attraction of SC machines. Subsequent experience revealed marked improvement in SC generator system interactions over those of conventional machines, and this aspect turned out to be particularly attractive to utility customers. The cryogenic aspects, although of concern, were not viewed as a limitation for utility consideration of LTS ac synchronous machines. The utilities, however, did view with great suspicion the overall operational implications of cryogenics, that is, the unlikely prospect that a generator using liquid helium could be constructed and operated with reliability and maintenance profiles identical to those of conventional generators. They viewed the added requirement for a refrigerator more as a reliability issue than as a cost or machine efficiency issue.

The U.S. effort on ac machines was essentially terminated in 1981 with the cancellation of the Westinghouse-EPRI (Electric Power Research Institute) 300 MVA program. The efforts on almost all of the SC generator and other power-related programs were also markedly curtailed at that time, which was largely a result of the decrease in interest and funding from the federal government and the unwillingness of industry to go forward on its own. Companies worldwide, except for those in Japan, almost collectively decided to reduce their effort and await further developments and an essential improvement in the marketplace created by increased electric power demand.

The Discovery of High Temperature Superconductivity

Technical development and demonstration for almost all of the various SC power applications was thus fairly well in place towards the end of the 1980s. Market conditions in the electric power sector, however, were fairly soft worldwide, which severely restricted the industry's ability to invest in new technology. Reluctance to invest in R&D, which was common in the United States, was not completely universal, and selected power-related development activities in SC continued to flourish. The Japanese officially launched their Super-GM program in September 1987, with a long-range objective of developing superconducting generators and other electric power applications that they expected to offer for sale to the utility market following the turn of the century (Ogawa 1992).

It was during this time period that the discovery was made of high temperature superconductors (HTS), which offered the advantage of cooling via liquid nitrogen instead of liquid helium. In the United States there was almost an immediate resurrection of interest in superconducting applications, with the Department of Energy (DOE) and Defense Advanced Research Projects Agency (DARPA) taking the lead in research and development of electric power applications. In 1988, DOE began its Superconductivity Program for Electric Power Systems, which primarily supported work at the national laboratories focused on development of wire and tape HTS materials for use in electric power equipment. This DOE program has evolved into the present effort, established in 1993, called the Superconductivity Partnership Initiative (SPI), which is helping to fund the industrial development of electric power components using HTS materials. The DOE SPI program initiated four industry-led projects directed at development of key superconducting electric power applications:

1. demonstration by Lockheed Martin of a 2.4 kV distribution level fault-current limiter
2. construction by Reliance Electric of a 125 hp ac synchronous motor
3. development led by General Electric of ac generator technology
4. development led by EPRI of a 115 kV transmission cable

These four projects also teamed with one or the other of the two major U.S. HTS wire and tape manufacturers, American Superconductor and Intermagnetics General, and with a utility that represented an end user. DOE recently awarded Phase II programs to develop "precommercial" prototypes to Reliance Electric for a 5,000 hp motor and to Lockheed Martin for a 15 kV-class fault-current limiter.

Advantages of High Temperature Superconducting Coils

The advantages offered by HTS wire or tape over conventional LTS materials that rely on liquid helium may not be completely obvious. For some applications, the overall impact on efficiency of HTS technology due to operation at liquid nitrogen temperature may be insignificant in comparison to LTS technology operating at liquid helium temperature. For example, for a large (>100 MVA) ac synchronous machine, the impact on the machine efficiency derived from the 25-50 times reduction in refrigerator power consumption offers no major economic advantage; even complete elimination of refrigerator power consumption would only show an improvement in machine efficiency of ~0.02% for a 300 MVA rating (Blaugher 1996). Of more importance than the efficiency improvement is that use of a liquid nitrogen ambient would lead to reduced capital costs for the refrigeration plant and reduce the complexity of the cryogenic design. Even more important would be the projected improvement in the entire cryogenic system with respect to reliability.

The performance of an HTS superconducting coil in a liquid nitrogen environment would show unparalleled stability compared to LTS performance. If copper is assumed to be the stabilizer for an HTS conductor, the resulting specific heat for the conductor would be approximately three orders of magnitude higher than for a conventional 4.2 K copper-stabilized LTS conductor. Thus, the HTS conductor would be inherently more stable, even with a possible reduction in current sharing caused by the increase in resistivity for the copper matrix. In addition, the critical heat flux, i.e., the peak nucleate boiling or transfer from nucleate to film boiling, is higher for 77 K liquid nitrogen than for liquid helium by over an order of magnitude. These combined thermal properties would further enhance the operational stability for an oxide coil over comparable LTS construction. It would thus be possible to maintain adiabatic stability at filament sizes several orders of magnitude larger than those of LTS conductors. The ability of HTS conductors to tolerate conductor movement due to Lorentz forces would also be improved over LTS conductors (Blaugher 1996).

These factors also contribute to the HTS coils being more tolerant of ac loss. Increased ac loss tolerance follows as a result of the ability to tolerate larger temperature excursions during ac transient events, which would be mostly applicable to the ac synchronous generators and motors. Exposure to steady state ac currents, as experienced for the transmission line and transformer, would continue to demand a low-ac-loss conductor to minimize the heat load and maximize the operating efficiency. The small efficiency improvement of 0.1-0.2% for these applications would be negated if high ac losses were exhibited.

Required HTS Performance and Cost

Table 2.2 compares various electric power applications with regards to the HTS wire or tape performance requirements for prototyping and eventual commercialization, as defined by the industry. (The current, field, and mechanical performance requirements could apply equally to LTS conductors.) The operating temperatures listed apply only to HTS wire; LTS coils normally operate at 4.2-8 K.

The last column of Table 2.2 lists the cost target for HTS conductors in $/kAm. Cost considerations follow directly from the earlier observation that an SC coil is cost-effective only if the amp-turns for a given coil or cable show a marked advantage over ordinary copper conductor. At present, the cost for conventional LTS Nb-Ti wire is ~$2/kAm; Nb_3Sn costs two to five times more, depending on whether the conductor is multifilament or tape. The lowest cost listed in Table 2.2 for HTS systems, $10/kAm, would thus be consistent with the cost of Nb_3Sn and is judged by most industry experts to be acceptable for all electric power applications. The present cost estimate for Bi wire, which has far lower performance levels than Nb_3Sn, is at least 1 to 2 orders of magnitude higher than the cost estimate for Nb_3Sn. The present high cost of HTS conductors is not likely, however, to limit attempts to construct and demonstrate the various applications, which is born out by recent successful tests of an HTS transmission line (Scudiere et al. 1996), HTS fault-current limiter (Leung et al. 1996), and HTS synchronous motor (Schiferl, Zhang, Shoykhet et al. 1996; Schiferl, Zhang, Driscoll et al. 1996). The commercialization, i.e., market price, for all of these applications demands that the lowest price be offered in order for the SC components to be cost-competitive with conventional nonsuperconducting devices (Bray 1995).

Table 2.2
High Temperature Superconducting Applications: Industry's Wire Performance Requirements

APPLICATION	**INDUSTRY-DRIVEN DEVICE GOALS**							
	J_c (A/cm^2)	Field (T)	Temp$_{op}$ (K)	I_c (A)	Wire Length (m)	Strain (%)	Bend radius (m)	Cost ($/kAm)
Fault-current limiter	10^4 - 10^5	0.3-3	40-77	10^3 - 10^4	1,000	0.2	0.1	10-30
Large motor (1,000 Hp)	10^5	2-4	25-77	100-500	1,000	0.2-0.3	0.05	10
Motor (125 Hp)	1.5 x 10^4	1.0	27	75-80	~300		0.01	10-100
Generator (100 MVA)	5 x 10^4 [a]	4-5	20-50	500-1,000	500-1,000	0.2	0.1	10
SMES (1 MWh)	10^5	5-10	20-77	10^4	1,000	0.2	1	2-5
Transmission cable	10^4 - 10^5	<0.2	65-77	25-30 [b]	100	0.4	2 [c]	10-100
Transformer	10^4 - 10^5	0.1	20-77	200-1,400	1,000	0.2	0.2	10

a. Current density for individual high temperature superconducting filaments
b. Current for individual wire; distribution cables, with multiple wires, require current near 10 kA
c. Cable requirement

Table 2.3 compares the key parameters that utilities will use when evaluating the purchase of an SC power device against existing or alternative technologies. This table compares all of the current SC power-related applications with respect to system performance, reliability and maintenance, efficiency, operating lifetime, and installed cost against representative competing technologies.

Although each individual utility will approach its needs differently and conduct its evaluation of a given component according to different priorities, and other unlisted parameters such as environmental impact may also guide decisionmaking; nevertheless, certain concerns appear to be significant for all utilities. The electric utilities are extremely sensitive to cost, and stated life-cycle cost is one of the most important elements in their evaluation. Operational requirements must also be consistent with their normal way of doing things, i.e., servicing and maintenance procedures should be similar to their normal practice. Coupled with this last requirement is the reliability and maintenance cost factor for the component, which must be comparable to that of their present equipment. The utilities must be able to integrate and service these new SC components, with some modest additional training, using existing power station or utility personnel. The maintenance cycles must also be comparable with standard utility practice. Advertised efficiency improvements, although universally desirable, are admittedly uncertain, due to insufficient operating experience; thus, the industry perception is that promoters cannot accurately predict a reliability and maintenance profile.

The SC or cryogenic applications should, in principle, offer a longer operating lifetime than their conventional counterparts. All of the conventional technologies commonly experience degradation to the insulation due to thermal aging, which should be insignificant for the cryogenic applications. The insulation in an SC rotor for a generator or motor should not degrade; hence, the usual rewinding maintenance should not be required during its 30-40 year operating lifetime.

Table 2.3
Comparison of Superconducting Electric Power Applications to Conventional Technologies

Superconducting Electric Power Applications	System Performance	Reliability & Maintenance	Efficiency	Operating Lifetime	Installed Cost [1]	Competing Technology
AC synchronous generators	Improved steady state and transient	Must be equivalent	Higher by 0.5-1.0%	Longer	Equal or higher	Gaseous and liquid-cooled
AC synchronous motors	No change	Must be equivalent	Higher by 1.0 to 2.0%	Longer	Higher	Induction and addition of VSD
AC underground transmission	Ability to double the rated capacity	Must be equivalent to conven. undrgd.	Slightly higher	Longer	Higher	• Cu/Al • "FACTS" • extruded
Fault-Current Limiters for transmission & distribution	Reduces transient currents on system components	Comparable to circuit breakers	More efficient T & D system	Longer than circuit breakers	2 to 10x circuit breaker	• Solid State breakers • Reactors • "FACTS"
Transformers for transmission & distribution	No change [2]	Must be equivalent to conven. transf.	Slightly higher by 0.1-0.2% [3]	Longer	Higher	• Iron Core
Storage Superconducting Magnetic Energy Storage (SMES)	Improves power quality and conditioning, spinning reserve, VAR & AGC	Comparable to other T&D components	Most efficient storage technology	Longer	Higher	• Flywheels • VAR Comp. • Batteries • STATCOM • Capacitors

1. Includes unit cost, siting, and system support, i.e., refrigeration, power conditioning, etc., compared to conventional cost
2. May require additional components, i.e., circuit breakers and/or current limiters
3. Requires low ac loss conductor

In the absence of thermal aging, life-cycle costs for the generator or motor improve accordingly. The life-cycle costs, as currently applied by the utilities, include the total capital and installation cost, all operating costs, all known maintenance costs such as rotor and armature rewinds, and annual inspection and refurbishing; the total is then depreciated over a 30- or 40-year lifetime. The overall plant cost, i.e., for the construction of the power plant, is also rolled up with the electric power components (generators, transformers, switch gear, etc.) to arrive at an overall life-cycle cost for the entire facility. As stated before, the success for SC applications is highly dependent on their ability to show life-cycle costs equal to or better than those of conventional components.

Utility people generally accept the predictions of higher efficiency and lower life-cycle costs for SC technology and completely understand their interdependence with reliability and maintenance. For this reason, system advantages over conventional components are key to obtaining utility interest in a given SC device. If the system performance offers enough of an incentive, utility staff will use this feature to justify the initial purchase cost and also explain to senior management the prospect for improved efficiency and lower life-cycle costs. The present tight fiscal climate as a result of deregulation may weaken the life-cycle argument, reinforcing the primary importance of the initial purchase price. A high-cost SC component thus may have a disadvantage compared to a conventional product.

Superconducting synchronous generators, underground transmission, and fault-current limiters all appear to offer unique system advantages along with reduced life-cycle costs. Superconducting underground transmission provides improved impedance-matching compared with conventional underground cable, which normally requires series/shunt compensation for lengths greater than 20 miles (Forsyth 1983, 285). It is not by accident that all of these highly favorable electric power components are currently under development by the DOE SPI program and Japan's MITI-sponsored SC programs.

AC ROTATING MACHINE EFFORTS IN JAPAN

Super-GM Program

Successful tests in Japan and the United States of ac superconducting synchronous generators, coupled with their predicted economic and performance advantages, convinced the Japanese government to launch a major national program in September of 1987 to develop technologies for applying SC to electric power apparatus. This program, called Super-GM (Engineering Research Association Project for Superconductive Generation Equipment and Materials), was specifically chartered to position the Japanese industry into a lead market position for advanced ac synchronous generators using superconducting windings. The initial goal for Super-GM was the design, construction, and test verification of three types of 70 MW-class superconducting generator model machine for establishing technologies to design and manufacture a 200 MW-class pilot machine suitable for commercialization. An additional goal was the parallel development of associated LTS and HTS conductors and related technologies such as refrigeration (Ageta 1996). It is important to note that the Super-GM program was not constrained to use HTS materials. The HTS development under Super-GM was also not specifically directed at an eventual retrofit requirement for the SC field winding. Completely different power applications were considered under the HTS activity: power cable, fault-current limiter, and power leads.

The Super-GM program is administered by the New Energy and Industrial Technology Development Organization (NEDO) as part of the New Sunshine Program of the Agency of Industrial Science and Technology (AIST) under the Ministry of International Trade and Industry (MITI). Super-GM, as a true national program, involves 16 member organizations with representation from the electric utilities; manufacturers of electric power equipment; companies involved in both LTS and HTS research and manufacture of wire and tape; refrigeration and cryogenic suppliers; and independent research institutes such as the Central Research Institute of the Electric Power Industry (CRIEPI). Additional support on collaborative research and consulting is provided by universities and national research organizations such as MITI's Electrotechnical Laboratory (ETL), which has provided basic research and technology assessment. CRIEPI has also assisted Super-GM with benefit and system analysis and electrical analysis for the stator and rotor. NEDO provides direct funding to the Super-GM organization, located in Osaka, in support of the generator design, construction, and test; the conductor research on both LTS and HTS; the refrigeration system; and total system integration and testing. Super-GM is also exploring other electric power devices beside the generator as part of the overall materials effort.

The 1996 budget for Super-GM was approximately $26 million, down from a peak in 1995 of $39 million. The manpower for the total effort averaged approximately 250 people/year in the preceding five years. Nearly $254 million was funded by AIST/MITI from 1988-1996. This figure has been complemented by additional support from the member companies in what amounts to cost-sharing ranging from 20-50% of the contracted amount. The salaries for the technical staff assigned to the Super-GM organization in Osaka, for the most part, are directly paid by the individual companies. Most staff members are rotated from the member companies on a two- to three-year basis.

The Super-GM program entered in 1996 the final installation, testing, and verification phase for the 70 MW-class superconducting generator model machine development. As of April 1997, the machine was undergoing adjustment at the verification test facility prior to verification test; cool-down of the SC rotor with low temperature He gas and liquid helium was to be initiated shortly thereafter. The test facility for the model machine, constructed at Kansai Electric's Osaka power station, is pictured in Fig. 2.1 and shown schematically in Fig. 2.2. Construction, started in June 1994, is now complete. The first rotor (designated "slow response excitation type A") and the "common" stator, both constructed by Hitachi, were delivered and installed in early 1997, with plans for five months of testing starting in June 1997. Following the Hitachi rotor, the Mitsubishi Electric rotor ("slow response B") and the final ("quick response") rotor built by Toshiba will be installed and tested. Testing of the three rotors is scheduled through 1998. The Nb-Ti conductor for these three rotors was supplied, respectively, by Hitachi Cable (for the slow response excitation type A), Sumitomo Electric (for the slow response B), and Furukawa Electric (for the quick response).

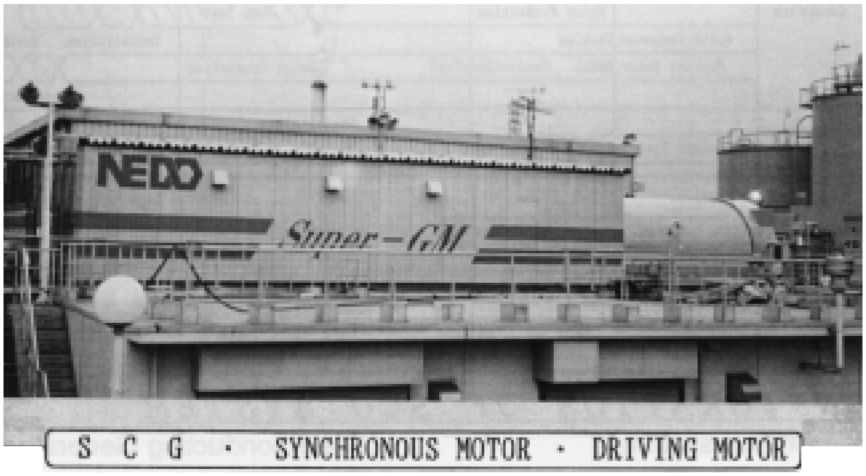
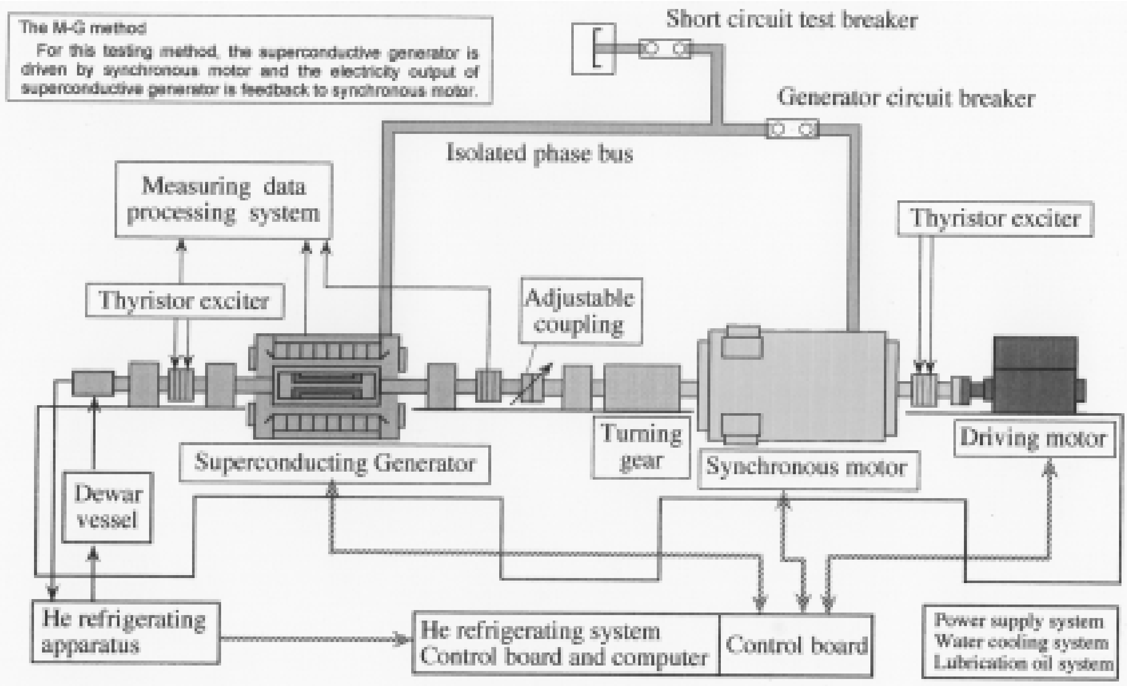


Fig. 2.1. External view of the Super-GM test facility at Osaka Power Station.


The M-G method

For this testing method, the superconductive generator is driven by synchronous motor and the electricity output of superconductive generator is feedback to synchronous motor.

Fig. 2.2. Super-GM superconducting generator testing schematic.

As shown schematically in Fig. 2.2, the Osaka verification test facility will use a back-to-back motor-generator (M-G) test method with the addition of an induction motor to bring the M-G system up to synchronous speed, compensate for the combined M-G losses, and maintain synchronous speed. The helium refrigeration system, constructed by Mayekawa Manufacturing, is a 100 ℓ/hour closed cycle turbine-expander, screw-compressor system. External liquid nitrogen is used for additional precooling in the high temperature cold box heat exchanger. A preconditioning liquid helium Dewar is used as a buffer to supply liquid to the generator. The liquid helium is introduced into the rotor by means of a helium transfer coupling. The first rotor and stator from Hitachi are undergoing adjustment at the test site. The final testing of the second rotor has been completed at the Kobe works of Mitsubishi Electric. The testing of the first rotor at Hitachi was reported at the August 26-30, 1996, Applied Superconductivity Conference in Pittsburgh, Pennsylvania (Yamaguchi, Takahashi, and Shiobara 1996). These rotating test results indicate that the cooling for the saddle pole SC field winding should be cryostable, due to the supercritical state for the helium, obtained under rotation, combined with the open winding design. The field winding is also well constrained, due to use of a slotted winding, conventional wedges on the straight sections, and retaining rings in the end turns. The cryostable design, along with the good mechanical positioning and the use of both cold and warm electrothermal damper shields, should show high transient capability for the generator during full load testing.

Generator Benefits and Market Projections for Super-GM

The 70 MW-class Super-GM machine is considered a “model” to establish technologies for future design and manufacture of a 200 MW-class “pilot” generator. Provided the 70 MW test is completely successful, a future program targeted at 200-300 MW would be considered. It is anticipated that the costs of an SC and a conventional machine would be nearly identical at a 200-300 MW rating, using a 20-year lifetime. At the time of the WTEC visit, Super-GM managers felt that the major advantage of SC generators was related to “performance advantages for the power system,” specifically with respect to steady state and transient stability, improved reactive power capability, and improved ability to tolerate negative sequence fields. Also, Super-GM researchers estimated that SC generators would lead to a ~30% increase in the power transfer limits of the transmission system. Additional economic benefits were an expected 0.5-1% increase in efficiency and a ~50% reduction in size and weight. Use of SC generators would also provide environmental advantages due to reduced oil consumption and reduction of CO_2 emissions. The Super-GM market forecast for SC generators, with introduction expected by 2005, using only the national market for Japan, was estimated at $440 million/year with 20-30 units in the 200-600 MW range and two units at 1 GW.

Super-GM LTS and HTS Wire and Tape Research

Since 1988, Super-GM research on superconducting wire and tape in support of power apparatus development has been conducted in parallel with generator research on both LTS and HTS conductors. The LTS effort has primarily focused on development of low ac loss conductors for three different applications: an armature winding manufactured by Furukawa Electric; a shunt reactor manufactured by Sumitomo Electric; and a fault-current limiter manufactured by Hitachi Cable. Three different types of Nb-Ti stranded wires with ~0.1 µm filaments and a Cu-Ni matrix have been developed by the manufacturers for their respective applications. The conductors have showed reduced ac losses with an acceptable current-carrying capacity of 2-3 kA.

Approaches for obtaining low ac loss Nb_3Sn have also been followed, involving 6 different manufacturing processes:

1. Bronze Process (Furukawa)
2. Internal Tin (Sumitomo Electric)
3. In-Situ (Fujikura)
4. Tube (Showa Wire and Cable)
5. External Diffusion (Hitachi Cable)
6. Powder Metallurgy (Kobe Steel)

The Nb_3Sn conductors, in general, have not proved to be as good as the Nb-Ti conductors, having nearly one order of magnitude higher hysteresis loss than the Nb-Ti. The transport current is also lower than Nb-Ti at 1-2 kA. The normalized ac quench current at 50 Hz under a dc magnetic field of 0.5 T is roughly equivalent at 200-500 A_{rms}/mm^2 for both the Nb-Ti and the Nb_3Sn conductors. The Nb-Ti in general has showed a lower ac loss than the Nb_3Sn at 50 Hz, ± 0.5 T. The Super-GM HTS research on oxide wire and tape development is oriented primarily at a future ability to apply HTS conductor to power applications, including SC generators. The realization of an HTS conductor would simplify the cryogenic design. The basic design approach for an HTS rotor would be nearly identical to an LTS design.

The HTS wire effort, which also started in 1988, was at the time of the WTEC visit making progress using 6 approaches (Yoshida et al. 1996; Chiba et al. 1996):

1./2. *Progress in Long Wire Research*

- Furukawa has used a "multipipe" method for fabricating Bi-2223 to produce 300 m, I_c = 4.4 A with a low Ag ratio of 1.3. A Bi-2212 tape of 250 m was fabricated by rolling using Bi-2212 laser pedestal rods and silver matrix; a 100 m test length showed ~5 A at 77 K.
- Hitachi has produced a 100 m, thallium-free precursor on 50 µm Ag tape. Subsequent thallination has produced a Tl-1223 thick film with I_c of ~5 A at 77 K for a 10-meter length.

3. *Progress in Large Current Research*

- Sumitomo has fabricated a Bi-2212 laser pedestal rod with an I_c value of 4.1 kA at 77 K.

4. *Progress in High Current Density Research*

- Fujikura has reported using laser deposition on a polycrystalline metal tape with a biaxial aligned YSZ buffer layer. J_c of ~1.1 x 10^6 A/cm^2 was observed at 77 K and just over 10^5 A/cm^2 at 5 T. A long length of ~1 m also showed 2.1 x 10^5 A/cm^2 at 77 K.

5./6. *Progress in Large Area Deposition Research for Fault-Current Limiters*

- Toshiba has reported using ionized cluster beam deposition of Y-123 on $SrTiO_3$ that showed I_c of 60 A.
- Mitsubishi Electric has reported using a CVD technique to make Y-123.

AC ROTATING MACHINE EFFORTS IN THE UNITED STATES

Reliance Electric DOE SPI Motor Program

Reliance Electric and EPRI started a joint program in 1987 to evaluate the use of HTS materials in electric motors. This initial program, which included American Superconductor Corporation (ASC) as the HTS conductor supplier and coil manufacturer, eventually was transitioned in 1994 into a DOE SPI program. The SPI program also included Centerior Energy, representing the end user, and Sandia National Laboratory, which assisted Reliance on the cryogenic cooling system analysis. The focus for the SPI program was demonstration of a "model" air core ac synchronous motor using HTS windings that would be scaleable to larger ratings suitable for commercialization.

In February 1996, Reliance Electric successfully tested a four-pole, 1,800 rpm synchronous motor using HTS windings operating at 27 K, at a continuous output of 200 hp (see Fig. 1.2, p. 5). The HTS coils, manufactured by ASC using Bi-2223 tape, achieved currents of 100 A at 27 K, which is 25% over the initial goal of 80 A. The current density at 100 A corresponds to 7,500 A/cm^2 in the SC wire. The peak field achieved by the four coils during the testing was nearly 1 T. Rotating tests at different speeds (600 rpm and 1,800 rpm) did not show any change in performance for the coil current, indicating good mechanical capability and acceptable cryogenic cooling for the HTS coils (Schiferl, Zhang, Shoykhet et al. 1996; Schiferl, Zhang, Driscoll et al. 1996).

Fig. 2.3 shows a cross-section of the rotor, illustrating the placement of the HTS coils and cryogenic cooling scheme. This rotor design, which is similar to designs used for SC ac generators, has a number of key features (Schiferl, Zhang, Shoykhet et al. 1996; Schiferl, Zhang, Driscoll et al. 1996):

- the vacuum jacket includes the use of multilayer insulation
- torque tubes (at each end of the rotor) are cooled by exhaust gas
- the rotor drive end is demountable, allowing access to cryogenic space to allow coil changing and modification of the cooling scheme
- the rotor cold space and coils are fully instrumented to measure stresses, temperature, pressure, and magnetic field levels

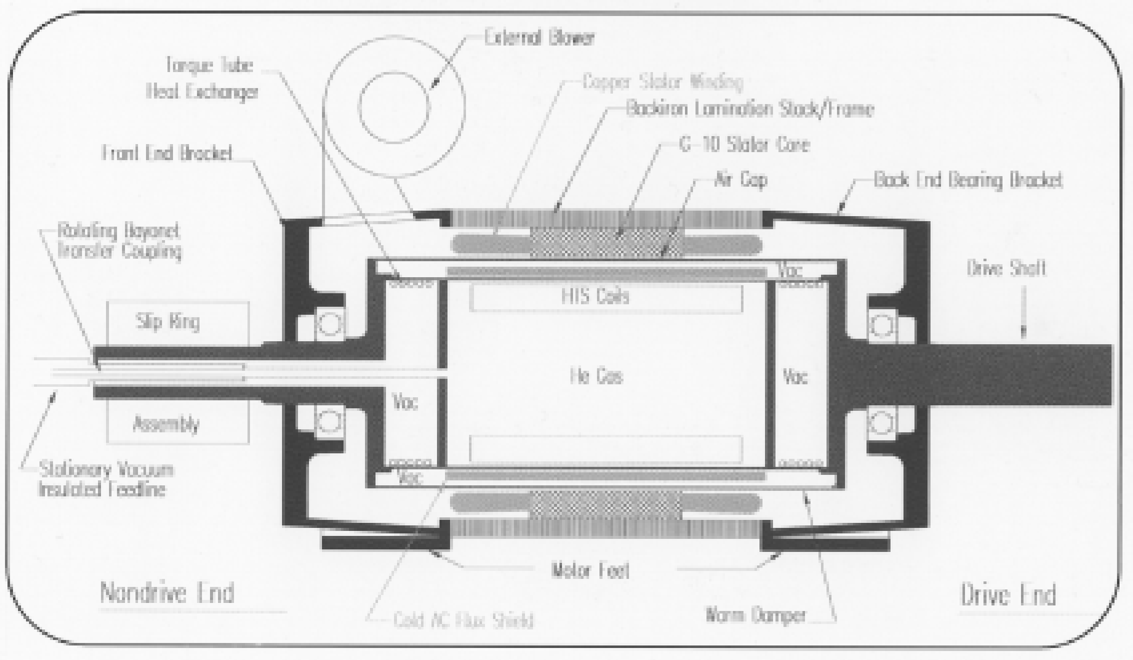


Fig. 2.3. Cross-section of Reliance Motor showing HTS coils and cryogenic system.

In August 1996, the Reliance-led program was extended by DOE into a Phase II SPI effort to develop a precommercial prototype of an HTS motor at a 5,000 hp rating. This motor, combined with an adjustable speed drive (ASD), will offer marked efficiency improvement and more operational flexibility than conventional induction motors; specifically, the motor speed will be able to be properly matched to changing load requirements. Superior performance and energy efficiency compared to conventional induction motors should make the HTS motor extremely attractive to customers and highly competitive in the marketplace for large motors above 1,000 hp. The 5,000 hp motor with ASD should show an efficiency exceeding 98%, which is ~2% higher than that of a conventional motor (Schiferl, Zhang, Shoykhet et al. 1996; Schiferl, Zhang, Driscoll et al. 1996). The impact of refrigerator power on the efficiency for a motor operating at 77 K should result in a ~0.1% decrease, giving an efficiency improvement of 1.9%. Reducing the operating temperature from 77 K to 30 K would decrease efficiency by an additional ~0.2%, yielding a net efficiency improvement of 1.7%. This estimate is based on an assumption of ~100 W heat removal at 30 K and a refrigerator coefficient of performance of 0.10, which would require approximately 10 kW of refrigerator power. In contrast to ac generators at ratings of 200-400 MW, which are much larger than the 5,000 hp motor, which corresponds to 3.73 MW, the refrigerator power has a much more severe impact on motor efficiency, giving an incentive to operate at higher temperatures near 77 K. If operation at 30 K is necessary due to HTS characteristics, the net efficiency improvement of ~1.7 % is still likely to be attractive for the 5,000 hp application.

General Electric DOE SPI Generator Development Program

Another DOE SPI program on SC ac synchronous generators was carried out by a General Electric Company (GE) team made up of engineers from its research laboratory and its Power Generation Engineering and Power Systems Engineering departments. The GE program, initiated in 1994, was directed at the conceptual design and assessment of a 100 MVA generator and the development of an HTS racetrack coil suitable for use in a full-scale generator. A more complete description of the GE program is presented in an article in *Advances in Cryogenic Engineering* (Lay, Herd, and King 1996), which discusses the program objectives; the early coil development; related HTS conductor activities on Bi-2223 tape; and the alternate HTS conductor, Tl-1223 tape, which offers improved temperature and field capability over Bi-2223. The complete details on the development, fabrication, and final testing of the racetrack coil is reported in two companion papers presented at the August 1996 Applied Superconductivity Conference (Herd et al. 1996; Salasso et al. 1996). The Bi-2223 tape for this racetrack was supplied by Intermagnetics General Corporation (IGC), which was the HTS wire and tape manufacturer and key partner on the GE/SPI program. The Argonne National Laboratory also supported IGC on the Bi-2223 development. Additional national laboratory support to GE and IGC was provided by Oak Ridge National Laboratory and Los Alamos National Laboratory.

The racetrack coil, shown in Fig. 2.4, is cooled by a heat exchanger wound external to the surface of the epoxy-impregnated coil. Helium gas, from a closed-cycle helium refrigerator, is circulated through the heat exchanger to maintain steady state temperature control at test temperatures of 20 K and 25 K. The racetrack coil achieved 34 A at 25 K, corresponding to ~40,000 ampere-turns, which is sufficient for consideration in a generator application (Herd et al. 1996). Additional tests on the ac loss and transient capability were also extremely positive. GE researchers concluded, “The capability of 20 K (and higher temperature) HTS coils to deal with current overdrive transients of many times I_c is remarkable. Much higher transient heating can be tolerated than for the previous generation of LTS generator designs” (Salasso et al. 1996). This conclusion supports the earlier comments in the section Advantages of HTS Coils (p. 12) on the use and limitations of liquid-helium-cooled LTS coils for generator applications.

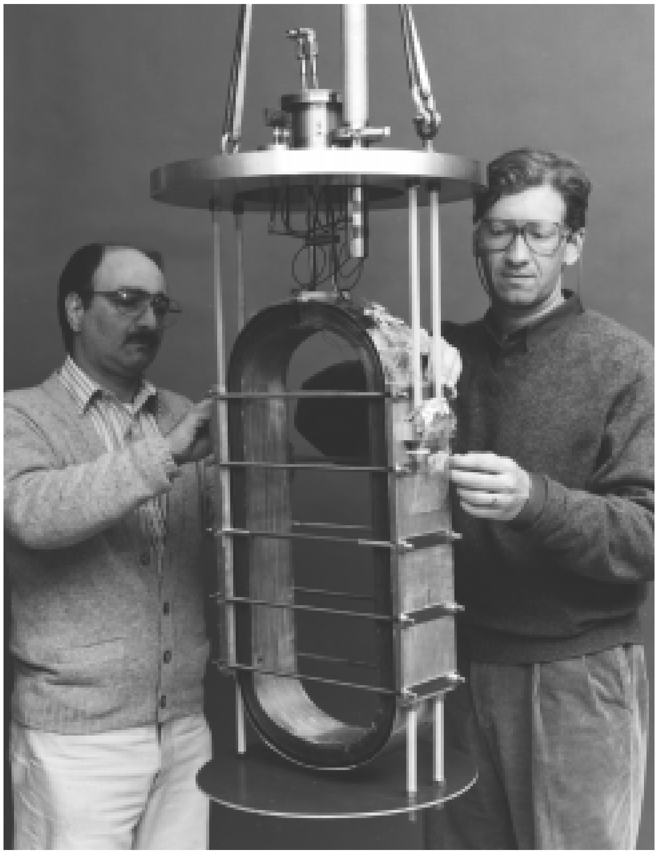


Fig. 2.4. General Electric prototype Bi-2223 racetrack coil for generator application.

MAGNETIC ENERGY STORAGE EFFORTS IN JAPAN

Integrating energy storage into an electric power system has long been recognized as a way to maximize a utility’s generation and/or transmission capacity. Electric power can be stored during off-peak periods and then recovered during high-peak conditions to offset the need for larger generation or expanded transmission capacity. In Japan, load-leveling or diurnal usage of stored energy is currently accomplished at pumped-storage installations, which are considered to be fairly inefficient, having only ~70% turn-around efficiency. Also, Japan's river system, highly dense settlement, and expensive real estate do not favor construction of additional pumped-storage facilities. The Japanese have thus been exploring alternative storage technologies, including SMES and flywheels. As discussed earlier, SMES research in Japan has been underway since the early 1970s, with many prototypes built and tested under actual "utility" conditions.

Japan's International Superconductivity Technology Center (ISTEC) conducted a three-year feasibility study starting in 1988 on electric power apparatus, including SMES, under a program sponsored by MITI's Agency of Natural Resources and Energy. As part of this study, the Subcommittee on Energy Storage recommended in 1989 the detailed design using available technology of a small-scale SMES, with either a solenoid or toroidal field configuration, that would be consistent with future R&D efforts (Katsuya 1990). This SMES program, much like Super-GM, did not mandate using HTS materials; thus, LTS conductors such as Nb-Ti and Nb_3Sn were the primary choice. Demonstration of a small-scale SMES, whose size is closely related to that needed for power system stabilization, would also address many major technical issues facing the large-scale diurnal storage SMES, such as ac losses, power conditioning, and refrigeration. ISTEC's initial SMES effort was followed by a six-year program started in 1991 to implement the construction and test of a small-scale SMES pilot plant at a 100 kWh/20 MW rating. This ISTEC program, also sponsored by MITI's Agency of Natural Resources and Energy, involves Toshiba as the primary magnet manufacturer, the Electric Power Development Corporation providing power conditioning, and various utilities led by Chubu Electric with additional support from Tohoko and Kyushu Electric Power Companies (Kamiyama 1994).

The design approach for the 100 kWh/20 MW system, shown in Fig. 2.5, is a toroidal magnet with an outside diameter for the cryostat of ~12 m (Kamiyama 1994). A half-size prototype coil was constructed by Toshiba and had been recently tested at the time of the WTEC trip to Japan. The test coil used a forced-flow Nb-Ti cable-in-conduit conductor and demonstrated 20 kA at 2.8 T, which is the rated current for the basic design. The initial testing was conducted at the Japan Atomic Energy Research Institute (JAERI), with further tests planned at Lawerence Livermore National Labs (LLNL) in the United States. Additional information on this SMES program is presented in the ISTEC, Chubu, and Toshiba site reports (Appendix C).

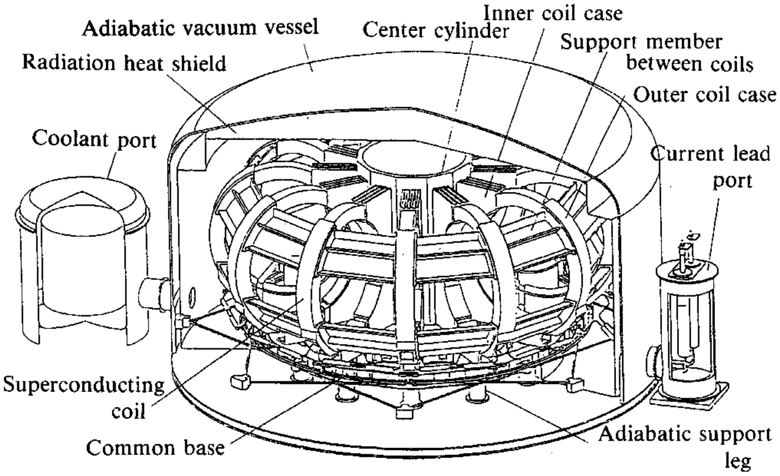


Fig. 2.5. Conceptual design of the ISTEC superconducting coil for the 100 kWh small-scale SMES.

Another program looking at the use of SMES for power system stabilization has been led by Kansai Electric Power Company (KEPCO). A small three-coil torus (400 kJ per coil), shown in Fig. 2.6, was assembled and tested on the KEPCO power system through a transformer and chopper arrangement. Two of the coils were built separately by Sumitomo Electric and Mitsubishi Heavy Industries using Nb-Ti conductors (SuperCom

1996). The third coil, built by Mitsubishi Electric, used Nb_3Sn. This program also involved Osaka University, which with KEPCO looked at how SMES could be used for power system control and stabilization (Tada, Mitani, and Tsuji 1995, 250).

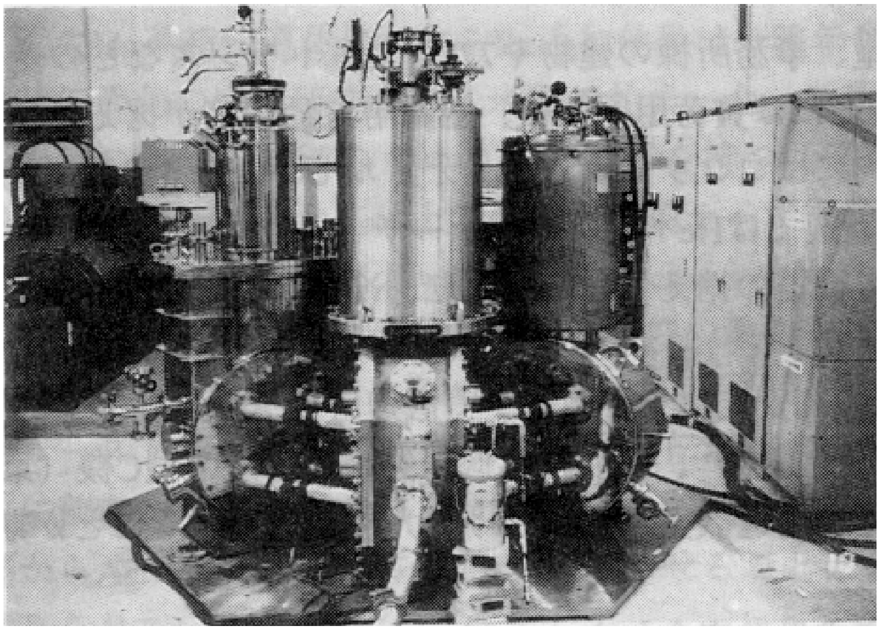


Fig. 2.6. KEPCO 3-coil torus (400 kJ per coil).

MAGNETIC ENERGY STORAGE EFFORTS IN GERMANY

The most active effort on SMES in Germany is carried out at the Forschungszentrum Karlsruhe (FZK) laboratory. FZK is constructing a 250 kJ SMES with a toroidal field design to address a power quality problem due to the frequent startup of large motors at a saw mill. Analysis indicates that a SMES system would be ideal for reducing this flicker problem, due to its fast response capability. FZK is also investigating at the Deutsches Electronen Synchrotron (DESY) laboratory the use of SMES as a pulse power source for providing ~10 GW pulses with a 1.0 ms duration at a 10 Hz rate in order to power rf klystrons (Jungst 1995).

At Siemens, the interest in SMES over the last few years has been mostly restricted to design and evaluation studies, with no current plans for development or construction. Siemens, RWE (the largest German utility), and Preussen Electra have completed an evaluation and conceptual design of a 2 MWh/50 MW SMES for use in providing frequency stabilization to the electric system. SMES continues to be of interest, but recent economic studies by Siemens indicate it may be too expensive compared to other storage technologies (Prescher et al. 1995).

It is thought that using HTS current leads, which are now a commercial reality and can be purchased from a number of manufacturers including Hoechst and ASC, would reduce the heat leak in a SMES system. Use of HTS conductors to fabricate a high field, high density SMES is also projected as an interesting future application. An HTS SMES operating at 10-20 T would require a “composite conductor” capable of carrying thousands of amperes with low ac losses to minimize heating for multiple charge and discharge cycles.

The Technical University of Munich has also been conducting research on SMES and is constructing a 1.4 MJ toroidal field system using LTS conductors (Lorenzen et al. 1995).

At ABB in Switzerland, energy storage is considered an important area; it has been strongly followed in the past, and an LTS SMES has been constructed for experimental evaluation. At the time of the WTEC visit, a major SMES system using LTS conductor under development for the Swiss railroad had been terminated due to realization of an alternative, less costly, solution. ABB had no plans for SC storage but did plan to continue to evaluate the technology.

MAGNETIC ENERGY STORAGE EFFORTS IN THE UNITED STATES

The most significant program on energy storage in the world is being carried out by Babcock and Wilcox (B&W) in the United States. This ~$50 million program is cost-shared by industry (70%) and the federal government (30%) through DARPA. B&W will construct and install a 500 kWh SMES primarily to provide spinning reserve to the Anchorage Municipal Light and Power (AML&P) utility. The Anchorage utility is part of the “Alaskan Railbelt System,” one of the most isolated utility networks in the United States. The Anchorage area served by AML&P uses almost half of the railbelt system’s peak load, which reaches approximately 600 MW during winter. AML&P is required as part of the railbelt interconnection agreement to designate ~30% of its generating capacity for spinning reserve; part of this reserve is provided by a hydroelectric facility at Bradley Lake. Physical restrictions at Bradley Lake result in dispatch time for this hydro capacity of approximately one minute or more, too long a time to prevent additional load shedding during an event such as a generator outage, which would lead to frequency instability on the system, resulting in programmed load shedding. The planned SMES system will instantly dispatch ~30 MW over a period of ~1 minute, which will provide sufficient time to ramp up the hydro capacity and put it on line to prevent further load shedding. As designed, the SMES will store 1,800 MJ in a low-aspect solenoid almost 7 m in diameter using an aluminum-stabilized Nb-Ti conductor operating in a “cryostable cooled” mode (Huang et al. 1995).

Several U.S. companies are producing small SMES systems, called micro-SMES, primarily to provide power quality improvements to selected customers rather than as grid or network solutions. These ~1 MW units with a few MJ stored energy are commercially produced by Superconducting, Inc. (SI), of Madison, Wisconsin, and by IGC of Latham, New York. SI and IGC have supplied micro-SMES systems to the United States Air Force (USAF) as part of a program to provide uninterruptable power capability and power conditioning, primarily for voltage stabilization, to selected USAF control centers. At present this “power quality” market is also served by battery storage or flywheel systems, especially in Japan and Germany. Outside of the United States there is no comparable activity for micro-SMES commercialization.

SUMMARY

The Japanese Super-GM program to develop SC generators represents the major activity worldwide directed at the commercialization of superconductivity in an electric power application. This conclusion is based on the duration of the program, the total money invested by industry and the Japanese government, and the number of institutions and people involved. The future for this program, however, is highly dependent on the “complete” success of the planned testing through 1998 on the three rotor configurations for the generator. The follow-on program to construct a 200 MW-class pilot machine is also highly dependent on a significant improvement in the market forecast for this generator. Without an increase in demand, it is quite likely that even with unqualified success for the generator tests that Japanese industry may not be willing to commit the necessary cost share to go forward with the program. Interest in using HTS conductors in this future program will depend on progress in achieving higher transport properties at higher fields.

The current U.S. DOE SPI program on the development of an HTS synchronous motor is unique.

The B&W “spinning reserve” program with Anchorage Municipal Light and Power is the world’s largest SMES program and provides an acceptable performance and cost-effective solution to a utility problem.

CONCLUSIONS

Substantial progress has been made over the past 30 years toward the eventual acceptance and integration of SC power components into the electric power system. High critical currents in superconductors have been demonstrated and manufactured, with the “older” LTS materials offering lower cost and improved manufacturability. HTS superconducting magnets have also been fabricated and successfully applied to a limited range of electric power applications, which have operated at temperatures as high as 50 K. SC power applications have definitely shown promising features — improved system performance and projected lower life-cycle costs are the key parameters of interest to utilities. Commercialization and utility acceptance of these devices is ultimately dependent on their ability to obtain reliability and maintenance profiles comparable to those of conventional devices and on their ability to compete cost-effectively in the marketplace with conventional technology. The operational advantages and hoped-for improvement in reliability of HTS materials over LTS materials are the key factors for HTS integration. Use of HTS wire and tape in power devices is ultimately dependent on achieving acceptable performance — i.e., in current, field, mechanical tolerance, and cost — which has not yet been totally realized. This performance limitation will not prevent the fabrication and demonstration of HTS power components that are underway in the DOE SPI program; however, commercialization will dictate that both performance and cost issues be completely satisfied.

In the United States, the development thrust to build and introduce SC power devices is presently compromised by the reality that the majority of U.S. industrial companies are not able or willing to commit substantial R&D support to this technology. Coupled with this industrial constraint is the limited funding available from the federal sector, with only DOE and EPRI providing budgetary support specifically for SC power development.

Following the excitement of the HTS discovery, the U.S. Office of Technology Assessment conducted a study, published in 1988, *Commercializing High Temperature Superconductors*. It is fair to say that the recommendations for substantial federal funding for superconductivity, especially related to electric power development, have not been realized. It is also fair to say that one of the major concerns raised, that is, that “The scientific race is becoming a commercial race, one featuring U.S. and Japanese companies, and one that the United States could lose,” is becoming even more serious as the 21st century approaches.

Congress in its FY98 budget deliberations has rallied to the need for expanded funding for SC electric power. This provides the United States with an enhanced ability to compete worldwide in this exciting new technology, which by 2030 could show widespread integration of superconducting components throughout the electric power system. Assuming modest market penetration over the next decade, the energy savings in fuel costs alone for motors and generators would approach ~$1.0 billion/year (Adelman and Blaugher 1993). The combined market for SC applications, which is ~$2.5 billion in 1995, could rise to nearly $100 billion by 2010 and double to ~$200 billion by 2020 (ISIS 1993). (These market projections are highly dependent on a projected increase in demand for capacity early in the next century, which is controversial.) U.S. utilities at present are in a “holding pattern” because of concern as to how they will be affected by ongoing deregulation. For the most part, they are deferring investment in expanded capacity for generation or transmission. Most of this uncertainty should be resolved by 2000, by which time the utilities are likely to need new generation and transmission equipment.

The Japanese especially are betting that this need will occur. Government planning in Japan is highly committed to advanced technology, as evidenced by the substantial government support for research on superconductivity. Most of this commitment is shared by the Japanese industrial sector, as evidenced by its willingness to cost-share most of the government programs. It is very clear, however, that the Japanese industrial companies will only continue to do this if their internal market projections and return on investment are consistent and support their research investment.

It is hard to predict what economic and environmental factors and other changes may occur globally or in the United States in the next decade to impact electric energy demand. Effects of deregulation on U.S. utilities and on the generation, transmission, distribution, and cost of electricity is unclear. The experience of large utilities in California, the first state to be deregulated, indicate that consumer costs will go down. Utilities and power brokers then may look for the improved performance and greater efficiency offered by superconductivity. In the United States, a number of utilities servicing major cities such as Los Angeles are considering the mandated use of electric vehicles, which should result in an increased need for intracity electrical capacity. Energy-efficient superconducting electric power technology thus would be poised to move forward with the development and demonstration of SC power devices to dramatically improve the electric power industry.

It is anticipated that the power system of the future will look like the Advanced Power System shown in Fig. 1.1, p. 2, with widespread use of SC generators and motors, transmission, fault-current limiters, and SC energy storage.

REFERENCES

Adelman, S., and R.D. Blaugher. 1993. Assessment of energy benefits and market potential for superconducting technology for electric power. Paper presented at the International Superconductivity Industry Summit in Kobe, Japan.

Ageta, T. 1996. R&D project on superconducting generators in Super-GM. In *Proc., ICMC/ICEC 16* (Kitakyushu, Japan, May 20-24).

Appleton, A.D. 1975. *IEEE Trans. on Magnetics* Mag. 11: 633.

Berlincourt, T.G. 1987. *IEEE Trans. on Magnetics* Mag. 23.: 403.

Blaugher, R.D. 1996. Superconducting electric power applications. In *Advances in cryogenic engineering.* Vol. 42. ed. L.T. Summers. New York: Plenum Press.

Blaugher, R.D., T.J. Fagan, J.H. Parker, Jr., J. Wells, and J.L. McCabria. 1974. A high speed superconducting generator. In *Proc., ICEC* (Kyoto, Japan, May): 143.

Bray, J.W. 1995. *J. Electronic Mat.* 24: 1767.

Chiba, M., M. Kakamata, H. Chiba, N. Yoshida, and T. Ichikawa. 1996. Paper presented at ICEC 16 in Kitakyushu, Japan, May 20-24. To be published in the conference proceedings.

Edmonds, J.S. 1979. Superconducting generator technology — an overview. *IEEE Trans. on Magnetics* Mag. 15: 673-79.

Forsyth, E.B. 1983. *The Physics Teacher* (May): 285.

Forsyth, E.B., and G.H. Morgan. 1983. *IEEE Trans. on Magnetics* Mag. 19: 652.

Fujino, H. 1983. *IEEE Trans. on Magnetics* Mag. 19: 533.

Fujita, H. 1989. *Proc., 2nd International Symposium of Superconductivity* (ISS'89) (Tsukuba, Japan).

Funaki, K., M. Iwakuma, and K. Yamafugi. 1988. *Proc., ICEC 12* (Southhampton, England).

Glebov, I.A., and V.N. Shaktarin. 1983. *IEEE Trans. on Magnetics* Mag. 19: 541.

Herd, K.G., L. Salasso, E.T. Laskaris, R.A. Ranze, C.G. King, P. Haldar, and J.G. Hoehn. 1996. *IEEE Trans. on Magnetics*, Applied Superconductivity Conference (Pittsburgh, PA, Aug. 26-30).

Huang, X., S.F. Kral, G.A. Lehman, Y.M. Lvovsky, and M. Xu. 1995. *IEEE Trans. on Applied Superconductivity* 5: 428.

Hulm J. K., and R.D. Blaugher. 1961. *Phys. Rev.* 123: 1569.

Ishigaki, Y., H. Shirahama, and K. Kuroda. n.d. *Hitachi Review* 35(3): 165.

ISIS (International Superconductivity Industry Summit). 1993. Kobe, Japan: Council on Superconductivity for American Competitiveness (CSAC).

Jungst, K.-P., 1995. *Supraleitung in der Energietechnik II*, VDI-Verlag: 133.

Kamiyama, K. 1994. *ISTEC Journal* 7: 39.

Katsuya, H. 1990. *ISTEC Journal* 3: 42.

Kunzler, J.E. 1987. *IEEE Trans. on Magnetics* Mag 23: 396.

Kunzler, J.E., E. Buehler, F.S.L. Hsu, and J.H. Wernick. 1961. *Phys. Rev Lett.* 6: 89.

Larbalestier, D.C. 1990. Introduction to Superconducting Materials section of *Metals Handbook*, Vol. 2, 10th ed. Materials Park, OH: American Society of Metals.

Laskaris, T.E., and K.F. Schoch. 1980. *IEEE Trans. on Power Apparatus and Systems,* PAS- 99: 2031.

Lay, K.W., K.G. Herd, and C. King. 1996. A 100 MVA generator utilizing HTS windings: Design assessment and component development. In *Advances in cryogenic engineering.* Vol. 42, ed. L.T. Summers. New York: Plenum Press.

Leung, E.M.W., G.W. Gilbert, M. Dew, P. Gurrola, K. Muehleman, B. Gamble, C. Russo, G. Dishaw, H. Boenig, D. Peterson, and A. Rodriquez. 1996. HTS fault current limiter for utility applications. In *Advances in Cryogenic Engineering.* Vol. 42, ed. L.T. Summers. New York: Plenum Press.

Lorenzen, H.W., V. Brammer, J. Meinke, F. Rosenbauer, J. Schaller, and R.M. Schottler. 1995. *Supraleitung in der Energietechnik II*, VDI-Verlag: 149.

Office of Technology Assessment (U.S.). 1988. *Commercializing High Temperature Superconductors.* Washington D.C.: U.S Office of Technology Assessment.

Ogawa, T. 1992. *ISTEC Journal* 5:38.

Parker, J.H., Jr., R.D. Blaugher, A. Patterson, P.D. Vecchio, and J.L. McCabria. 1975. A high speed superconducting rotor. *IEEE Trans. on Magnetics* Mag. 11: 640.

Prescher, K., W. Nick, H.-E. Vollmar, M. Kleinmaier, and U. Radtke. 1995. *Supraleitung in der Energietechnik II*, VDI-Verlag: 115.

Raju, B.P., and T.C. Bertram. 1982. *IEEE Proc.* 129: 166.

Rogers, J.D. 1981. *IEEE Trans. on Magnetics* Mag. 17: 330.

Rogers, J.D., H.J. Boenig, R.T. Schermer, and J.F. Hauer. 1985. *IEEE Trans. on Magnetics* Mag. 21:752.

Salasso, L., K.G. Herd, E.T. Laskaris, H.R. Hart, and M.V.K. Chari. 1996. *IEEE Trans. on Magnetics,* Applied Superconductivity Conference (Pittsburgh, PA, Aug. 26-30).

Schiferl, R.F., B.X. Zhang, B.A. Shoykhet, D.I. Driscoll, A. Meyer, J. Zevchek, E. Johnson, B. Gambell, C. Prum, J. Boccio, J. Picard. 1996. Paper presented at the American Power Conference in May. To be published in the conference proceedings.

Schiferl, R.F., B.X. Zhang, D.I. Driscoll, B.A. Shoykhet, and R.C. Dykhuizen. 1996. Development status of a 125 hp superconducting motor. In *Advances in cryogenic engineering.* Vol. 42, ed. L.T. Summers. New York: Plenum Press.

Scudiere, J.D., D.M. Buczek, P. Miles, P. Roberts, D. Parker, P. Metra, M. Rahman, and D.W. Von Dollen. 1996. Development and demonstration of a HTS power transmission cable system. In *Advances in cryogenic engineering.* Vol. 42, ed. L.T. Summers. New York: Plenum Press.

Smith, J.L., Jr. 1983. Overview on the Development of Superconducting Synchronous Generators. *IEEE Transactions on Magnetics* Mag. 19: 522-28.

Smith, J.L., Jr., J.L. Kirtley, Jr., and P. Thullen. 1975 *IEEE Trans. on Magnetics* Mag. 11: 128.

SuperCom (in Japanese). 1996. Vol. 5, No. 1 (Feb.).

Tada, M., Y. Mitani, and K. Tsuji. 1995. *IEEE Trans. on Applied Superconductivity* 5: 250.

Thullen, P., J.C. Dudley, S.L. Greene, J.L. Smith, Jr., and H.H. Woodson. 1971. *IEEE Trans. Power Apparatus and Systems*, PAS-90: 611.

Wang, S.T., L. Genes, J. Gonczy, H. Ludwig, M. Lieberg, E. Kraft, D. Gacek, Y.C. Huang, and C.J. Chen. 1981. *IEEE Trans. on Magnetics* Mag. 17: 529.

Yamaguchi, K., M. Takahashi, and R. Shiobara. 1996. *IEEE Trans. on Magnetics*, Applied Superconductivity Conference (Pittsburgh, PA, Aug. 26-30).

Yoshida, N., K. Sato, J. Yoshitomi, and T. Ichikawa. 1996. Paper presented at ICEC 16 in Kitakyushu, Japan, May 20-24. To be published in the conference proceedings.

CHAPTER 3

POWER TRANSMISSION AND DISTRIBUTION CABLES & TRANSFORMERS

Robert S. Sokolowski

INTRODUCTION

The motivation for applying superconducting materials to a power transmission and distribution system is the promise of power delivery and conversion without the electric losses that result from I^2R or Joule heating. The period of 25 years from 1961 to 1986 saw considerable activity in development of power transmission cables using metallic or low temperature superconductors (LTS). Had it not been for the energy crisis of the early 1970s and the subsequent decline in energy demand, today there might be superconducting power transmission cables in use throughout the world. Target power ratings per circuit for superconducting cable systems dropped from 5,000-10,000 MW in the 1970s to 1,000 MW by the early 1980s (Engelhardt, Von Dollen, and Samm 1992). Although economic considerations continue to dominate the criteria for deciding whether a superconducting solution to electric power problems is appropriate, other factors are becoming increasingly important in the minds of decisionmakers. These include growing public concern over environmental issues and safety and the uncertain effects of deregulation on the generation and distribution of electric power. The responses to many of these issues will be known only after lengthy debate and no doubt countless pages of legislation. While the actual need for superconducting cables and transformers will be determined by local market conditions, aided perhaps by varying legislative requirements, the technology of superconducting systems is being developed globally, and competitors in the United States, Europe, and Japan who are looking for a stake in an anticipated multibillion dollar business are making excellent progress. When leaders in the field of superconductivity convened in Japan in May 1996 for the Fifth International Superconductivity Industrial Summit, they agreed that the world market for electric power devices based just on superconductivity will exceed $10 billion by the year 2010.

In spite of worldwide efforts to develop superconducting cables and transformers using LTS materials, the expense of cryogenic cooling systems for liquid He operation at 4.2 K with the strict operational reliability demanded by electric utilities, and the difficulty of developing a suitable low loss ac superconductor, presented seemingly insurmountable barriers to their introduction into the network. The discovery since 1986 of high temperature superconducting (HTS) materials in oxide-based systems with increasingly high transition temperatures has rekindled an interest in superconductivity in everyone in the power delivery chain, from generator to consumer. The operating temperature of HTS materials of up to 77 K (liquid nitrogen temperature) is considerably higher than the 4.2 K (liquid helium temperature) on which design of the LTS power systems of the 1970s and early 1980s was based. With higher temperatures come not only reduced refrigeration costs but also enhanced reliability.

SUPERCONDUCTING POWER TRANSMISSION CABLES — OVERVIEW

Although the energy crisis of the 1970s is now past and demand has increased considerably, the motivation for developing HTS power transmission cables comes primarily from the need to increase the power-handling capabilities of existing underground circuits, which are filled to capacity. HTS cables not only offer a doubling of the power per circuit, they also provide an environmentally attractive solution, because a leak in an underground HTS system would cause the benign release of nitrogen, whereas a leak in existing oil-filled high voltage cables could result in devastating soil contamination. Where oil-filled cables are used underwater, such leaks could produce even greater environmental damage.

Upgrading a power system by retrofitting existing ducts with HTS cables is most likely to occur in dense urban areas where the costs of trenching to install higher-capacity conventional systems would be prohibitive. In Tokyo, for instance, where demand for electric power is increasing at a rate of 2-3% per year, use of HTS cables is attractive since space is extremely limited and most underground ducts are filled to capacity. The opportunity in Tokyo alone provides a tremendous development incentive. There are ten large cable tunnels in Tokyo, each 20 km long and each containing three cables. If these cables were replaced with HTS cables at the rate of only one of the three cables in several tunnels each year, the project would require 600 km of cable and last ten years. The HTS conductor alone needed for such a venture would exceed 100 million meters and represent a business opportunity of several billion dollars. And if the relative economic value of the joints and terminations required for the cable follows today's pattern, then the business opportunity for these cryogenic components is at least ten times greater than that of the conductor business itself.

Development of LTS cables and cable concepts in the 1960s was pursued by industrial giants like Siemens, GE-France, BICC, and Westinghouse, and by several academic and government laboratories, including important contributions from the Technical University of Graz, Austria, and Brookhaven National Laboratory (BNL) in the United States (Giese 1993). In Japan, members of the MITI's Electrotechnical Laboratory carried out an economic study and concluded that superconducting cables were especially attractive for high power dc applications. Early testbeds used LTS materials in a variety of configurations.

In Germany, Linde studied the ac loss characteristics of rigid Nb tubes and built a 7-meter-long cryostat to measure these losses. Later the Linde team proposed a composite conductor of Nb, copper, and invar. In a collaborative program between the Technical University of Graz, AEG, Kabelmetal, and Linde (Munich), the superconductor was formed by coating the inner and outer walls of concentric corrugated tubes with a layer of Nb so that the layer on the outside of the smaller tube faced the Nb layer on the inside of the larger tube.

The BNL project employed Nb_3Sn superconducting tapes, and for the demonstration cable Intermagnetics General Corporation (IGC) manufactured a composite tape that had layers of copper, Nb_3Sn, Nb, and stainless steel. This work resulted in design of a 1,000 MVA, 138 kV, 4,200 amp system and in a preliminary solution to the problem of terminations. Progress in phase two of this work went well; however, the project was terminated for economic reasons.

HTS POWER TRANSMISSION CABLES — OVERVIEW

The major players in development of power transmission cables using high temperature superconductors are Pirelli and Southwire Corporation in the United States; Siemens, Pirelli, and BICC in Europe; and Sumitomo Electric Corporation, Furukawa, and Fujikura in Japan. Each of the major Japanese corporations manufactures its own HTS tapes. Siemens also manufactures its own HTS tapes, but it has also purchased material from others for use in earlier experiments. Pirelli has an arrangement with American Superconductor Corporation (ASC) that gives it exclusive access to ASC's tapes for use in power transmission cables. IGC also supplies high performance HTS tapes to this marketplace (Beales et al. 1996). All experimental and prototype HTS cables have been manufactured with multifilamentary tape containing the BSCCO-2223 compound.

The German government is providing half the funds (DM 20 million over three years) necessary to complete the cable program carried out and cost-shared by Siemens. In both the United States and Japan, on the other hand, the utilities are playing a major role in promoting the development of HTS cables. Tokyo Electric Power Company (TEPCO) provides nearly a million dollars annually to both Sumitomo and Furukawa to develop HTS cable prototypes and terminations, respectively. Chubu Electric Power Company has also worked with both Fujikura (Kume et al. 1995) and Sumitomo (Masuda et al. 1995) to develop related technology. In the United States, the Electric Power Research Institute, with some financial assistance from the Department of Energy, has invested heavily in power cable technology by forging a close alliance with Pirelli and ASC; total program costs are estimated to be $6 million over three years. Pirelli, Siemens, and BICC Cables have benefited from an earlier European collaboration, which included GEC, ABB, and Alcatel Cable, and which was financially supported by the European Commission under both the JOULE and BRITE-EuRAM initiatives.

The European project resulted in a very useful techno-economic study (Ashworth, Metra, and Slaughter 1993) that allowed individual members of the consortium to decide whether there was sufficient incentive to pursue further development of cable technology on their own. The significant conclusions of this study were (1) that for transmitted powers greater than 1 GVA, the HTS conductor's critical current density must exceed 200,000 A/cm^2 at liquid nitrogen temperatures in order for the overall costs to be comparable to conventional cables; and (2) that, in a 150 mm fixed diameter duct, an HTS cable can transmit up to seven times more power (to 700 MVA at 66 kV) at the same transmission cost.

HTS conductors, like so many other materials in their embryonic development phases, must exhibit improved performance and become less expensive if they are to gain widespread acceptance as articles of commerce. The Joule study presented a target performance-price window for HTS conductors (Fig. 3.1): for transmission of 400 MVA in a fixed diameter duct (believed to be an early application of HTS cables), the superconductor must carry in excess of 150,000 A/cm^2 if the price is about $40/meter. If the price falls to, say, $5/meter, the superconductor performance may be as low as 50,000 A/cm^2. For a given conductor price, say $5/meter, the "economic" critical current density is greater for application in a high power link than in a fixed diameter duct. This seems reasonable, as HTS must compete with the best available conventional cable solution in the former case, whereas HTS can be considered enabling in the latter.

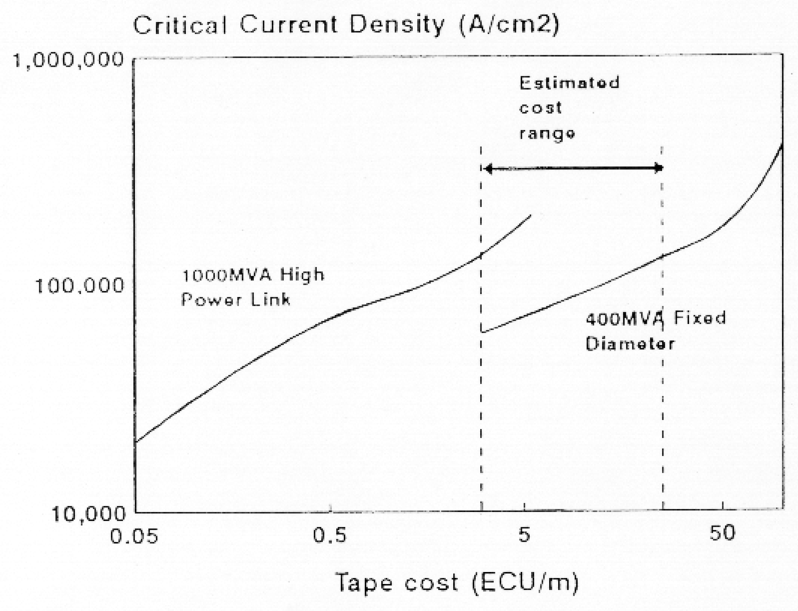


Fig. 3.1. Performance-cost limits from a "break-even" analysis (1 ECU ≈ $1.20).

HTS POWER TRANSMISSION CABLE DEVELOPMENT IN JAPAN

Of the major players in Japan that are developing HTS power transmission cables — Sumitomo, Furukawa, and to a lesser extent, Fujikura and Mitsubishi (Yuhya, Hosotani, and Hiraoka 1995) — Sumitomo Cable working with TEPCO has demonstrated the best performance in both fundamental materials development and cable construction. The configuration of its 7-meter cable prototype is schematically illustrated in Fig. 3.2, and the corresponding dimensions are shown in Table 3.1 (Shibata et al. 1995). Note that in this design the HTS tapes are used not only for transmission of the primary current, but also for shielding the external pipe from the magnetic fields generated by the tapes transmitting the power. This design increases the needed quantity of costly HTS conductor, but the lower electrical losses place less strain on the cryogenic systems, which reduces cooling costs. Several characteristics of this cable are as follows:

- 3-phase, 66 kV / 1 kVA$_{\mathrm{rms}}$ (114 MVA)
- 7 m length, 130 mm diameter
- magnetic shielding layer, PLPP insulated
- 3-phase continuous current test (1 kA$_{\mathrm{rms}}$, 7 hours)

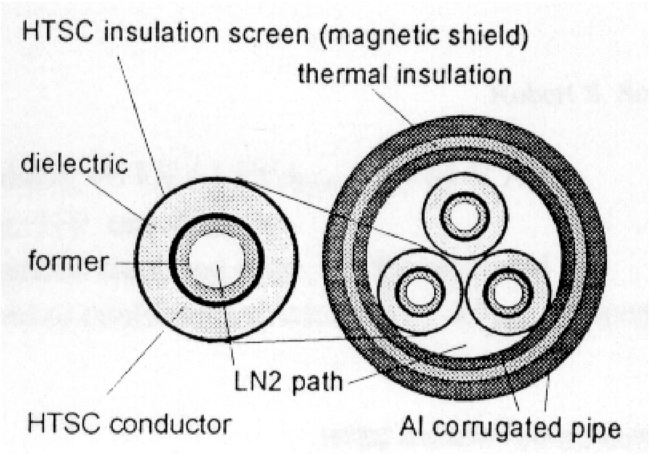


Fig. 3.2. Schematic of 7-meter HTS cable prototype (Sumitomo).

Table 3.1
Sumitomo/TEPCO Cable Prototype

	Size (mm)	Characteristics
Former	13 ID 19 OD	Al corrugated pipe Short current path
Conductor	22 OD	BSCCO-2223 HTSC
Dielectric	36 OD	LN$_2$ impregnated PPLP
Shield	38 OD	BSCCO-2223 HTSC 2-layers spirally wound Magnetic shield
Thermal Insulation	90 ID 130 OD	Superinsulation at vacuum Coaxial aluminum corrugated pipe

Table 3.2 gives characteristics of the Sumitomo HTS conductor used in assembling the 50-meter cabled conductor that is shown in Fig. 3.3.

Table 3.2
Sumitomo/TEPCO HTS Conductor

	Characteristics
HTS Tape	0.28 mm x 4.1 mm
Cabled Conductor	50 m long, 23 mm diameter 4 tape layers 2,900 A dc critical current at 77 K 2,200 A_{rms} ac transmission

Fig. 3.3. Fifty-meter-long cabled conductor coil.

The Sumitomo HTS tapes have a high cross-sectional aspect ratio. The self-field critical current densities are not as high as those cited as being “economic” in the Joule study; however, they are presently the best in the world and represent the state of the art for long-length HTS conductors. At 10^{-12} ohm * m and 10^{-13} ohm * m criteria, the I_cs of the conductor are 2,900 A and 2,200 A, respectively. It should be noted that it was the requirement of the utility sponsor, TEPCO, that the critical current density for its application (fixed diameter retrofit) be 100,000 A/cm^2. Lower critical current densities could only be tolerated if the attendant ac losses were reduced substantially. At the time of this WTEC study, ac losses were ten times higher than acceptable. Recent measurements on each of the four individual layers constituting this cable (see Fig. 3.4 for test layout) confirm that the ac loss is described by a self-field loss of a single cylindrical bulk superconductor based on the Bean model (Saga et al. 1996).

Fig. 3.4. View of power cable test layout.

Based on Sumitomo's cabled conductor characteristics, only four tape layers are needed to carry nearly 3,000 amps (dc critical current) at 77 K. With a tape width of 4.1 mm and a cable diameter of 23 mm, one can estimate that just over 60 tapes have been used to wind this cabled conductor, which means that the average I_c of one tape is approaching 50 A at 77 K! This is nearly ten times the I_c of the Furukawa cabled conductor described below and in Table 3.3.

- 1-phase, 66 kV / 1.4 kA_{rms} (38 MVA)
- 5 m, 124 mm diameter
- 66 kV - class terminations
- load test (1.4 kA_{rms}, 15 minutes)

In the Furukawa case, the J_c and the overall tape cross-section are nearly half of the Sumitomo values; consequently, one would expect an I_c at least four times smaller. Since ten tape layers were wound at a larger diameter than in the Sumitomo cable to produce a much smaller dc critical current at 77 K, the I_c is much smaller and is estimated to be about 5 A.

Table 3.3
Furukawa/TEPCO 50 m Conductor

HTS Tape Characteristics	0.185 mm x 3.3 mm 10,000 A/cm^2 at 77 K, self-field
Cabled Conductor Characteristics	50 m long, 38 mm diameter 10 tape layers 1,700 A dc critical current at 77 K 2,000 A$_{rms}$ ac transmission (flux flow regime)

Although there is not much published detail about the cable prototype proposed and assembled by Fujikura, it is unique in that it has HTS tapes lying axially along the cable length instead of being wound with a pitch (Kakimoto et al. 1995; Kume et al. 1995).

SUPERCONDUCTING TRANSFORMERS — OVERVIEW

Transformers represent one of the oldest and most mature elements in a power transmission and distribution network. From the point of electricity generation at a power plant, where extremely high voltages are needed to “push” large amounts of power into the grid, to the end user of electricity in a home or office, where typical appliances operate at much lower voltages (100-200 volts), transformers are needed to effect voltage conversions. At each conversion point, energy is lost, primarily in the form of wasted heat from changing electrical and magnetic fields in the copper (coil), iron (core), tank, and supporting structure. Even when the transformer is “idling,” so-called “no-load losses” (NLL) are generated in the core. Research over the last 50 years has succeeded in reducing NLL by a factor of three while increasing core costs by a factor of two. Recent substitution in distribution transformers (ratings below about 100 kVA) of amorphous metals for silicon iron core material has reduced NLL further, but this material has not been used in the cores of power transformers (ratings greater than 500 kVA). When a transformer is under a loaded condition, Joule heating (I^2R losses) of the copper coil adds considerably to the amount of lost energy. In spite of the fact that today’s utility power transformer loses less than 1% of its total rating in wasted energy, any energy saved within this one percent represents a tremendous potential savings over the expected lifetime of the transformer.

In a conventional power transformer, load losses (LL) represent approximately 80% of total losses. Of this load loss, 80% are I^2R losses. The remaining 20% consists of stray and eddy current losses. To date, efforts to reduce load losses have been directed toward the latter. Unlike copper and aluminum, superconductors present no resistance to the flow of dc electricity, with the consequence that I^2R losses become essentially zero, thereby creating the potential for a dramatic reduction in overall losses. In ac operation, the superconductor in an HTS transformer experiences a type of eddy current loss: both the heat produced by this loss (although extremely small in comparison to the energy lost in conventional materials) and heat conducted into the lower temperature regions of the superconducting transformer need to be removed through refrigeration. Even with the added cost of refrigeration, HTS transformers in the 10 MVA and higher range are projected to be substantially more efficient and less expensive than their conventional counterparts.

Motivation for developing superconducting transformers is not based solely on economic considerations of lowering total owning costs (initial capital cost + capitalized cost of load and no-load losses over the transformer’s effective life). With limited new siting availability in urban areas, the anticipated 2% annual growth in power demand means that existing sites must be uprated with higher power capabilities. Many existing sites are indoors or adjacent to buildings, which restricts the use of most oil-filled transformers. The inherent dangers of oil-filled devices are totally eliminated by application of superconducting technology where the only coolant required is benign (nitrogen as opposed to oil). Consequently, superconducting transformers operating either with a refrigerated coil or one cooled with liquid nitrogen pose no fire hazards and no threat to the environment comparable to that posed by leaks of flammable oils and toxic chemicals such as PCBs.

Serious interest in superconducting transformers began in the early 1960s as reliable low temperature superconductors based on Nb-Ti and Nb_3Sn became available. Analysis of the feasibility of such LTS transformers concluded that the high refrigeration loads required to keep the LTS materials at 4.2 K made the LTS transformers uneconomical. A major reduction in refrigeration costs and/or the discovery of materials that superconduct at much higher temperatures would be required to improve the economic attractiveness of these electric power applications. In the mid-1970s Westinghouse conducted an exhaustive design study of a 1,000 MVA, 550/22 kV generator step-up unit; it found that current transfer, overcurrent operation, and protection remained persistent problems.

Since 1980, development of LTS transformers has been conducted primarily by ABB and GEC-Alsthom in Europe and by various utilities, industries, and universities in Japan. Advances in production of long-length ultrafine multifilamentary Nb-Ti conductor and high resistivity Cu-Ni matrix materials have assisted in the reduction of ac losses. Feasibility of weight reduction and higher efficiencies has been demonstrated on smaller devices with ratings smaller than 100 kVA: single-phase 80 kVA (Alsthom), 30 kVA (Toshiba), and a three-phase 40 kVA (Osaka University). Larger units have also been constructed and tested successfully. A single-phase 330 kVA transformer built by ABB included provisions for fault-current limiting and quench protection. Kansai Electric Power Company reported the development of an LTS transformer utilizing Nb_3Sn conductor. One phase of this three-phase 2,000 kVA unit operated at 1,379 kVA without quenching and transferred fault current to parallel coils under quench condition.

HTS TRANSFORMERS — OVERVIEW

Immediately following the discovery of HTS materials in 1986, several studies looked into the feasibility of HTS transformers. Savings over conventional units were estimated to be greater than 35%, but the unknown ac loss characteristics of the HTS materials made it difficult to assess viable designs. A comprehensive study conducted for the U.S. Department of Energy found the life-cycle costs of an HTS transformer, on average, to be half those of a comparable conventional unit (Dirks 1993). National savings from the insertion of HTS transformers were estimated to be $25 billion through the year 2030. Over the size range of 30-1,500 MVA, Mumford (1994) estimated costs savings of HTS transformers over conventional designs to be as great as 70% and transformer weight to be 40% less.

A further advantage of HTS transformers over conventional units that is particularly relevant to Japan with its high population density is the inherently smaller size and weight of superconducting devices. As in the case of HTS power transmission cables that can provide increased capacity in existing ducts, HTS transformers can provide increased power handling in the same available space as a conventional power transformer. The benefits of smaller weight and size are expected to be major factors in the early introduction of HTS transformers in Japan. In Europe there is growing interest in using compact HTS on-board transformers in high-speed trains.

The potential market for superconducting transformers worldwide is in excess of a billion dollars. A review of the U.S. power transformer market shows that more than 90% of units are in the 10-100 MVA range (Table 3.4), representing 70% of the value of all transformers sold. The world market is estimated to be three to four times as large and growing at double the rate of the U.S. market.

There are three major HTS transformer projects currently ongoing in the United States, Europe, and Japan. Table 3.5 shows the team composition, size of the units under development, and the HTS materials used.

Table 3.4
Power Transformer Market, as of 1995-96

United States	**10-100 MVA**	**Over 100 MVA**
Units	874	78
MVA	33,000	26,000
$	$260 million	$109 million
World	3-4 times larger 2X growth rate	3-4 times larger 2X growth rate

Source: National Electrical Manufacturers Assn., modified to include transformer sales not tracked by NEMA.

Table 3.5
Major HTS Transformer Players

United States	Waukesha Electric - IGC (IGC) - 1 MVA prototype, 30 MVA design, Bi-2212
Europe	ABB (ASC) - 630 kVA prototype, 100 MVA design, Bi-2223
Japan	Fuji Electric - (Sumitomo) - 500 kVA prototype, Bi-2223

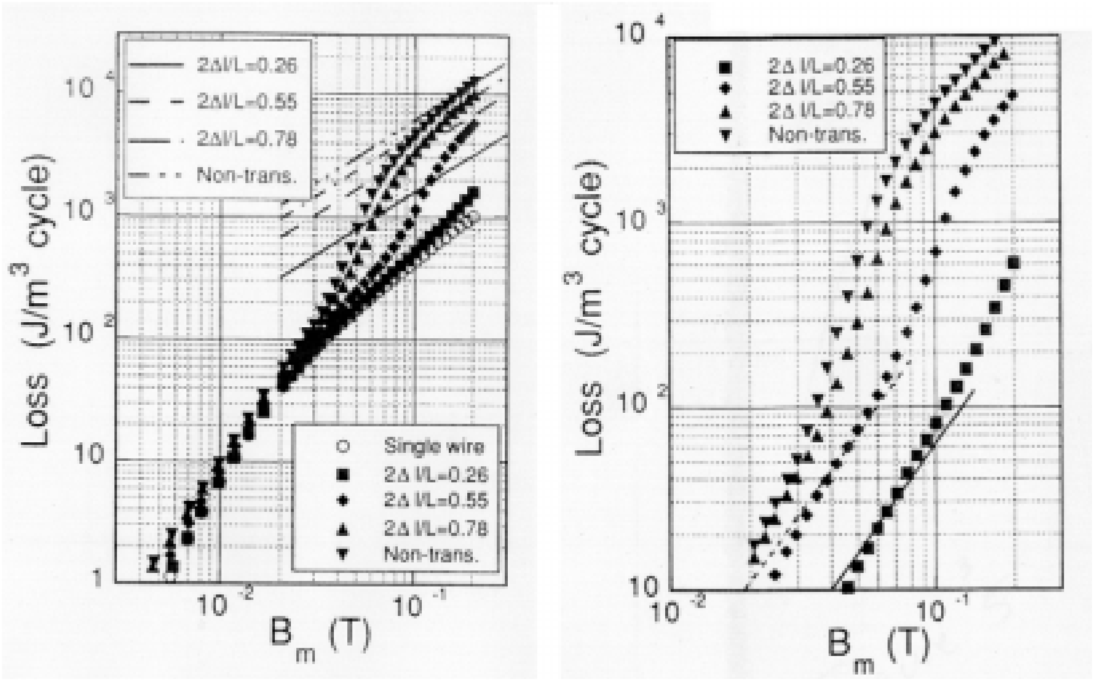
The U.S. effort was launched by IGC as an extension of a cooperative research and development agreement with the Oak Ridge National Laboratory. With Waukesha Electric (a division of General Signal) as a commercialization partner and with partial financial support and applications guidance from Rochester Gas and Electric, the IGC team has designed and is in the process of constructing a 1,000 kVA-class HTS demonstration transformer that utilizes a low-cost HTS-coated silver tape. Use of the BSCCO-2212 system ensures stable operation at temperatures as high as 30 K. Operation at 77 K is possible with the use of BSCCO-2223 conductors, but selection of the overall transformer design must weigh the benefits of reduced refrigeration loads due to the elevated operation temperature against the higher conductor costs due to use of the more expensive BSCCO-2223 material and the lower performance due to the increase in temperature. While the demonstration of the Waukesha-IGC transformer is intended for 1 MVA, the base design is targeted for 30 MVA, 138/13.8 kV, 60 Hz, 10% impedance at 18 MVA, Delta-Wye configuration.

ABB, in collaboration with Electricité de France, has used multifilamentary BSCCO-2223 tape produced by ASC to build a 630 kVA, 13.72/0.42 kV, 50 Hz, 4.6% impedance, Delta-Wye demonstration unit.

HTS TRANSFORMER DEVELOPMENT IN JAPAN

After Alsthom designed an LTS 220 kVA transformer and operated it successfully under a 70 kW load, many small-scale LTS units ranging from 10 kVA to 100 kVA were manufactured in Japan in order to confirm various aspects of basic operating behavior. Subsequently, larger units were built and tested by Nagoya University in conjunction with Takaoka (100 kVA), Kansai Electric in conjunction with Mitsubishi (2,000 kVA using Nb_3Sn), Osaka University in conjunction with Toshiba (40 kVA), and Kyushu University in conjunction with Toshiba (1,000 kVA). In addition to acquiring better understanding of the sensitivity of performance to changes in the critical design parameters, one of the more important results from these trials was acquiring better understanding of the stability of the ac conductor and the quench protection afforded by the particular design. Low ac losses were achieved in the LTS conductor through the use of twisted and transposed conductors having fine filaments and high resistivity matrices.

The HTS conductors available for use in transformers at the time of this study neither have fine (submicron) filaments nor are readily twisted and transposed, due to the somewhat brittle nature of the ceramic filaments. Moreover, the stabilizing material surrounding the filaments is composed of silver or silver alloy, which do not exhibit high resistivities. However, ability to operate at elevated temperatures makes it possible for the HTS conductors to tolerate higher ac losses than are tolerable in LTS systems, due to the large reduction in refrigeration costs. When LTS design parameters were used to estimate bounds of performance for HTS wires, Iwakuma et al. (1996b) concluded that an Ag-10%Au alloy sheath suffices for resistivity reduction, and that the filament diameter/thickness must be smaller than 25 microns and 10 microns for the case of round wires and flat tapes, respectively. They also determined that the ac losses of transposed Bi-2223 tapes are less than those of nontransposed tapes and about equivalent to the losses measured in single wires (Fig. 3.5).



(a) (b)

Fig. 3.5. (a) Total ac loss vs. B_m in the Nb-Ti single-wire and 2-strand parallel conductors; (b) The differences between the ac losses of a single wire and those of parallel conductors.

It is interesting to note that the Japanese industrial corporations that were involved in the development of LTS transformers have not reported activities in the area of HTS transformer development. Moreover, while the electric utilities are playing a pivotal role in transformer programs in the United States and Europe, the same is not true in Japan, where the driving force for development is in industrial and academic circles, with no apparent support from the utilities. At the CEC/ICMC meeting held in May 1996 in Kitakyushu, Japan, Kazuo Funaki (1996) of Kyushu University presented details of a 500 kVA HTS transformer program that was supported by the collaborative efforts of Fuji Electric and Sumitomo Electric Corporation (SEC). This author assumes that Sumitomo was principally responsible for supplying the HTS tapes, and that the majority of the transformer design and construction tasks were assumed by Fuji Electric and Kyushu University. Table 3.6 shows the characteristics of the HTS strands and the winding sequence. Note that the matrix is pure silver, not the silver-gold alloy recommended by Iwakuma, and that the filaments are not twisted, although there have been reports from other HTS wire manufacturers that it is possible to twist multifilamentary HTS conductors.

Table 3.6
Characteristics of the HTS Strands and the Winding Sequence, Fuji/SEC/Kyushu University HTS Transformer

Strand (Without Insulation)	
Superconductor	Bi 2223
Matrix	pure silver
Cross-section	0.22 x 3.5 mm
Number of filaments	61
Silver ratio	2.5
Twist pitch	infinite
Critical current	35 A at a self-field (criterion: 10^{-13} Ωm
Primary Winding	
Type	three-parallel
Number of layers	2
Number of turns	50 / layer
Number of transpositions	5 / layer
Secondary Winding	
Type	six-parallel
Number of layers	2
Number of turns	50 / layer
Number of transpositions	5 / layer

Design parameters of the 500 kVA unit (Fig. 3.6) are highlighted in Table 3.7, where the two values for the winding diameters refer to sandwiched layers that are constructed so as to reduce the effective self-field.

Results of the testing of this unit (Fig. 3.7) are summarized in Table 3.8.

Losses, estimated calorimetrically, amounted to 115 W, taking into account ac losses in the windings and heat leakage from the cryostat and current leads. Future plans for the Fuji/SEC/Kyushu University group's activities include changing the cooling method from pool boiling in liquid nitrogen to continuous flow of supercooled nitrogen with a refrigerator, with the intent of improving the current-carrying capacity of the winding and dielectric breakdown strength.

Fig. 3.6. Fuji/SEC/Kyushu University HTS transformer unit.

Table 3.7
Transformer Design Parameters (Fuji)

Capacity	500 kVA
Frequency	60 Hz
Voltage (primary/secondary)	6600 V / 3300 V
Current (primary/secondary)	76 A / 152 A
Core height/width cross-sectional area magnetic induction	silicon steel plate 1580 mm / 1110 mm 986 cm^2 1.7 T
Cryostat height diameter	GFRP 1210 mm 785 mm / 337 mm
Winding diameter (primary/secondary)	465, 553/509, 597 mm
Winding height	748 mm
Secondary load	500 kVA inductive coil

Fig. 3.7. View of transformer test setup.

Table 3.8
Transformer Characteristics (Fuji)

No-load test voltage (primary) exciting current no-load loss	 3300 V 2.60 A 2289 W
Short-circuit test voltage (primary) current (primary) % impedance	 44 V 75.8 A 0.67%
Load test maximum excitation level voltage (primary) current (primary)	 376 kVA 5700 W 66 A
Efficiency core loss ac loss in windings heat leakage	99.1% 2289 W 64 W x 20 51 W x 20

REFERENCES

Ashworth, S.P., P. Metra, R.J. Slaughter. 1993. Technical and economic feasibility of high temperature superconducting power transmission cables. In *Proc., First European Conf. on Applied Superconductivity*.

Beales, T.P., C.M. Friend, W. Segir, E. Ferrero, F. Vivaldi, L. Ottonello. 1996. A dc transmission cable prototype using high-temperature superconductors. *Superconducting Science Technology* 9: 43-47 (UK).

Dirks, J.A. 1993. *High-temperature superconducting transformer performance, cost, and market evaluation.* Pacific Northwest Laboratory Report PNL-7318 (September).

Engelhardt, J.S., D. Von Dollen, R. Samm. 1992. Application considerations for HTSC power transmission cables. In *Proceedings, Fifth Annual Conference on Superconductivity and Applications* (Buffalo, NY, Sept. 1991), 692-711. New York: Elsevier.

Fujikami, J., N. Saga, K. Ohmatsu, T. Shibata, S. Isojima, K. Sato, H. Ishii, T. Hara. 1995. Electromagnetic behavior of HTSC cable conductor in ac loading. In *Advances in superconductivity*. Vol. 8. Berlin: Springer-Verlag.

Funaki, K., et al. 1996. Design and construction of a 500 kVA-class oxide superconducting power transformer cooled by liquid nitrogen. In *Proc., ICEC16/ICMC Conference* (Kitakyushu, Japan, May).

Giese, R.F. 1993. *Superconducting transmission cables*. Argonne National Laboratory Report for the International Atomic Energy Agency (February).

Ise, T., Y. Marutani, Y. Murakami, E. Yoneda, R. Sugawara. 1995. Design and operating characteristics of superconducting transformer with simple configuration. In *Advances in superconductivity*. Vol. 8. Berlin: Springer-Verlag.

Iwakuma, M., et al. 1996a. Electromagnetic properties in parallel conductors composed of Bi2223 multifilamentary wires for power transformer windings. In *Proceedings, Applied Superconductivity Conference* (Pittsburgh, August).

Iwakuma, M., et al. 1996b. AC loss and current distribution in parallel conductors for Bi2223 HTS transformer windings. In *Proceedings, ICEC 16/ICMC Conference* (Kitakyushu, Japan, May).

Iwakuma, M., K. Funaki, M. Takeo, K. Yamafuji, M. Konno, Y. Kasagawa, K. Okubo, I. Itoh, S. Nose. 1996. A new concept for the composition of oxide superconducting wires for ac windings operating at LN_2 temperature. In *Proceedings, ICEC 16/ICMC Conference* (Kitakyushu, Japan, May).

Johnson, R.C., B.W. McConnell, S.P. Mehta, M.S. Walker. 1996. Status of superconducting power transformer development. Paper presented at the American Power Conference, April.

Kakimoto, K., S. Nagaya, N. Hirano, N. Hashimoto, M. Nagata, M. Nakagawa, N. Sadakata, T. Saito, 0. Kohno. 1995. Study for structure of power cables by Bi-2223 Ag sheathed tapes.

Kikuchi, H., K. Nemoto, S. Tanaka, Y. Tanaka, M. Suetsugu, T. Maeda, M. Yoshihara, H. Ishii, T. Hara. n.d. Flexible cable carrying superconducting current over 500A at 77K.

Kume, A., S. Nagaya, T. Shimonosono, M. Nakagawa, M. Nagata, N. Sadakata, T. Saitoh, 0. Kohno, M. Ono. 1995. Fabrication of the model cable using Bi-2223 Ag sheathed tapes.

Masuda, T., C. Suzawa, S. Isojima, T. Shimonosono, S. Nagaya. 1995. Development of the termination for the 77kV-class high T_c superconducting power cable.

Mumford, F.J. 1994. A techno-economic study of high Tc superconducting power transformers. International Conference on Electrical Machines, Paris, France, Sept.

Saga, N., J. Fujikami, K. Ohmatsu, T. Shibata, M. Watanabe, C. Suzawa, S. Isojima, K. Sato, H. Ishii, S. Honjo, Y. Iwata, T. Hara. 1996. Development of 5OM-long HTS cable conductor. Submitted for publication in the proceedings of the ISS'96 conference, Sapporo, Japan.

Shibata, T., J. Fujikami, S. Isojima, K. Sato, H. Ishii, T. Hara. 1995. Development of 3-phase 1 kA class high Tc superconducting power cable prototype. In *Advances in superconductivity*. Vol. 8. Berlin: Springer-Verlag.

Yuhya, S., K. Hosotani, M. Hiraoka. 1995. Prototype fabrication of power cable using Bi2223 Ag-sheathed superconducting tape.

CHAPTER 4

POWER SYSTEMS — OTHER APPLICATIONS

Robert Schwall

WHAT ARE “OTHER APPLICATIONS”?

Five topics complete the discussion of power applications of high temperature superconductors (HTS). Two of these, flywheels and fault-current limiters, are utility applications of superconductivity. Two, HTS leads and high field magnets, are non-utility, large-scale applications whose development will strongly impact the technology of utility applications. The final topic is cryogenic refrigeration, the development of which has a strong technological and economic impact on the application of HTS to utility problems.

FLYWHEELS

Diurnal Load Leveling

Demand for electric power has been increasing steadily, and as it increases, the gap between daytime and nighttime demand has been widening. Since generation capacity must be matched to peak demand, this situation has driven the construction of additional generation, transmission, and distribution infrastructure. Much of this infrastructure is only lightly utilized much of the time, leading to higher electricity rates. This situation is most acute in Japan, where demand for power is increasing more rapidly than in the United States. The most desirable solution, called diurnal or daily load leveling, is to have a mechanism for storing power during the night and feeding it back into the grid during the day. The basic idea is illustrated in Fig. 4.1.

In the United States, load leveling is addressed in some localities by building “pumped hydro” storage facilities. These consist of two water reservoirs or lakes at different elevations connected by a pump/generator station. During the night, water is pumped from the lower lake to the higher one using electric pumps. During the day, the water flows from the upper lake to the lower one, generating power. The overall efficiency of these systems is usually upwards of 80%, but their applicability is obviously tied to geography — there must be a suitable pair of lakes available. This is rarely the case in Japan, and another method of power storage is needed there. Ideally, this storage is located as close to the consumer as possible in order to decrease the peak demand on the transmission system as well as on the generation system.

Japanese Flywheel Energy Storage Program

To address this problem, two programs are active in Japan, the superconducting magnetic energy storage (SMES) program discussed in Chapter 2, and a program on superconducting flywheel energy storage. This focus on diurnal load leveling contrasts with U.S. SMES programs that focus on power quality improvement.

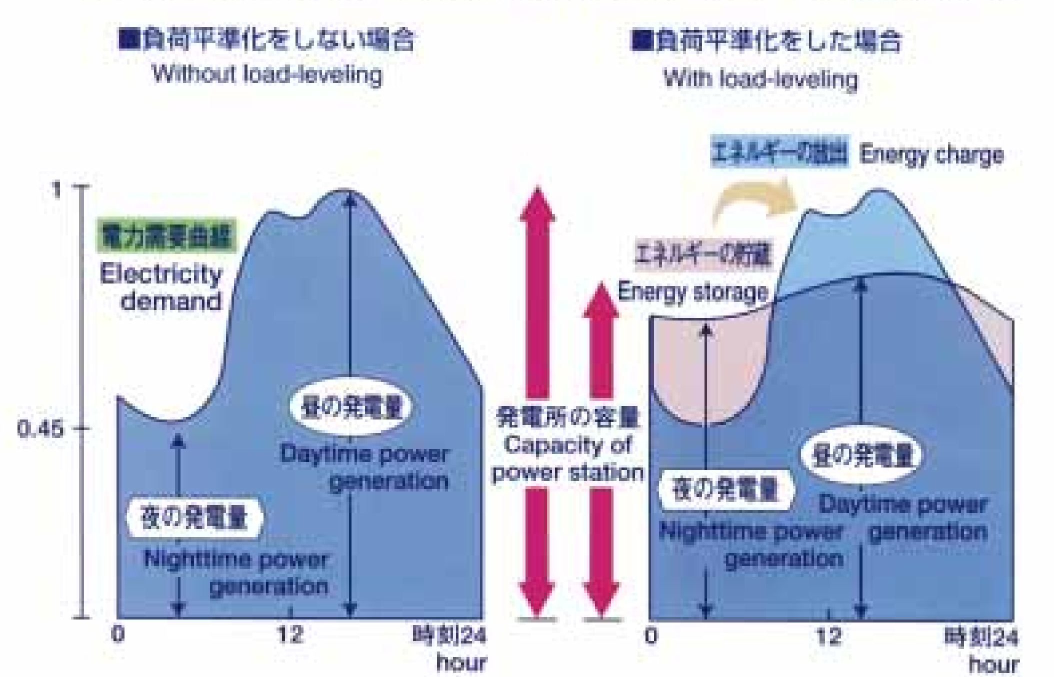


Fig. 4.1. The concept of daily load leveling by electric power storage system (NEDO n.d.).

Based on a systems-level analysis of the energy storage need, the Japanese flywheel effort has focused on storing energy at the substation level, rather than at the generating-site or end-user level. The required energy storage level is approximately 10 MWh, and because of the very limited availability of space in Japan, compactness of the flywheel system is a high priority. In 1995, the New Energy and Industrial Technology Development Organization (NEDO), part of Japan’s Ministry of International Trade and Industry (MITI), began a five-year program in superconducting flywheel energy storage that includes construction of a 10 kWh system in ~1999 and development of the component technology for the commercial 10 MWh system (Fig. 4.2).

The NEDO budget contained no funding for flywheels until FY 1995. The funding in 1995 was ¥300 million (~$3 million) and in 1996 was ¥500 million (~$5 million).

Program Content

The NEDO program addresses three areas:

1. the flywheel itself
2. the high temperature superconducting magnetic bearing
3. systems integration

Flywheel energy storage is not a new technology. In fact, it is widely used in industry in applications as diverse as punch presses and high field pulsed magnets. Its stored energy density (usually expressed in Watt-hour/kg) is, however, relatively low. In addition, its practical use has been limited to areas where the energy holding time is short because of the excessive rotational loss caused by bearings and windage. The NEDO program addresses the energy density issue through work on high-strength, high-speed flywheels and addresses holding time through development of a very low friction HTS magnetic bearing.

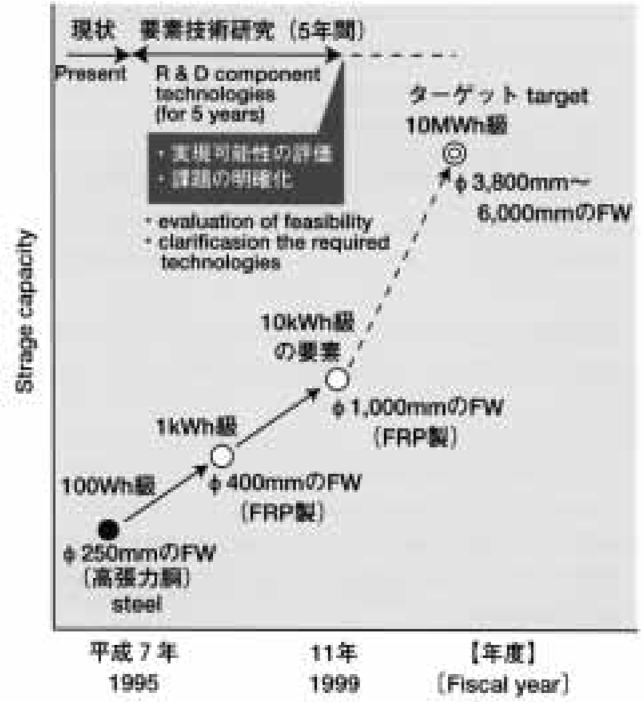


Fig. 4.2. NEDO's R&D schedule for flywheel energy storage (NEDO n.d.).

High strength, high speed flywheels. Most commercial flywheels are made of metal and rotate at relatively low speeds to maintain the tensile stresses in the flywheel within reasonable limits. Since the stored energy is directly proportional to the mass of the flywheel but proportional to the square of the rotational speed, increases in rotational speed yield a large benefit in energy density. Today's state-of-the-art flywheels therefore employ fiber-reinforced plastics (FRP) rather than metal. These materials can be engineered to have very high strength in the radial direction, thus permitting higher operational speeds. In addition, they can be designed to fracture into many small pieces in the event of a structural failure. This reduces the size of the required containment vessel and allows the system to be mounted above ground. (Safety considerations have led to designs of metal flywheel systems where the flywheel itself is underground). While the first demonstration flywheel in the NEDO program was made of steel, all subsequent devices will employ FRP. An additional benefit of the FRP flywheel, as seen in the following section, is that the lighter flywheel simplifies the design of the magnetic bearing.

Superconducting magnetic bearings. The primary factor preventing the application of flywheels to long-term energy storage is loss in the bearings. Any mechanical bearing with contact between the stationary and rotating parts will have enough loss to render the system uneconomical (Higasa 1994). One solution to the problem is to use a non-contact active magnetic bearing that employs conventional electromagnets. The rotational loss of such a bearing is 1-10% that of a mechanical bearing under the same operating conditions. The problem, however, is that the bearing itself consumes power, which is dissipated as heat in the copper electromagnets, and the bearing and cooling system power consumption must be included in the calculation of the overall system efficiency. A reasonable magnetic bearing consumes a few watts for each kilogram of flywheel weight, depending on the structure of the bearing and the control system, and this loss is sufficient to make a system using copper electromagnets uneconomical. Superconducting magnetic bearings, on the other hand, have demonstrated losses of 10^{-2} to 10^{-3} watts per kg for a 2,000 rpm rotor. This translates to an overall one-day, "round-trip" system efficiency of 84%, which is acceptable.

Figures 4.3 and 4.4 show the basic operation of the flywheel and bearing. The flywheel is at room temperature and carries on its lower surface a permanent ring magnet that rides above the superconducting portion of the bearing, which is simply an array of pellets of YBCO. The YBCO is kept at 77 K by an external supply of liquid nitrogen. The YBCO traps the magnetic flux produced by the permanent magnet, and as long as the pinning force of the YBCO is not exceeded, the bearing generates restoring forces to counter any relative motion of the permanent magnet and the superconductor. Thus, the bearing is completely passive and does not require the complex feedback and control circuits needed for conventional magnetic bearings.

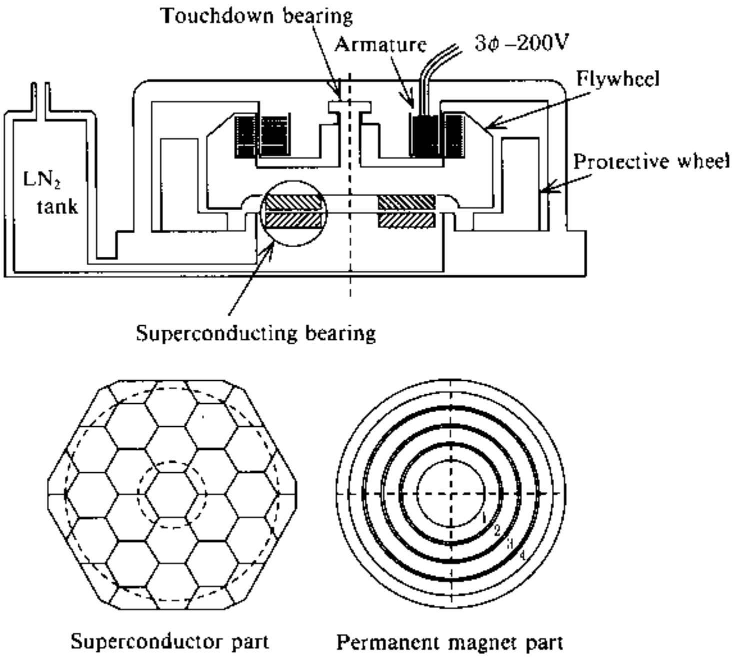


Fig. 4.3. Flywheel system and details of superconducting magnetic bearing assembly (Higasa 1994).

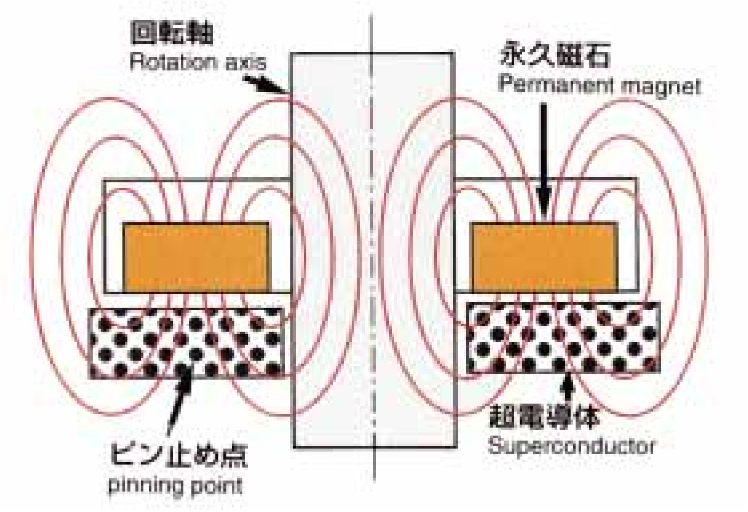


Fig. 4.4. Operation of the magnetic bearing (NEDO n.d.).

The development tasks for the bearing involve

1. increasing the pinning force of the YBCO to increase the mass of the flywheel that can be supported (presently the design target is 0.5 to 1.0 kg of flywheel per cm^2 of bearing surface)
2. refining the design of the magnetic bearing to reduce perturbations in the magnetic field seen by the superconductor when the flywheel rotates — such perturbations lead to loss in the superconductor and drag on the bearing

System integration. The flywheel program is in the early stages, and there appears to be no published work on Japanese plans for system integration. The superconducting bearing should, however, present no major challenges since the designs published show operation near 77 K and the expected heat loads are quite modest. They could be handled either by a liquid nitrogen supply or by integration of a single-stage Gifford McMahon cryocooler. The present target is an overall energy density of the flywheel of 100-200 Wh/kg. This is to be compared with a density of about 40 Wh/kg for lead acid batteries.

German Flywheel Energy Storage Program

In Germany, the Forschungszentrum Karlsruhe (FZK) directs a flywheel energy storage program that uses melt-processed YBCO for the bearings. FZK's Institut für Technische Physik (INFP) has advertised and offered for commercial sale semifinished cubes, cylinders, and rods of melt-processed YBCO. The institute has built and tested a 300 Wh flywheel model using superconducting bearings combined with permanent magnets. The flywheel system uses disks constructed from advanced carbon fibers. It was operated from 30,000 to 50,000 rpm and produced 10 kVA/300 Wh at 50,000 rpm. The electric drive system for the flywheel was developed in cooperation with the Institut für Elektrische Maschninen und Antriebe of Stuttgart University. The next step in the program is to develop a larger flywheel with a capacity of about 7 Wh/250 kVA, together with Siemens and accompanied by application studies with utilities. This flywheel will probably be a "stacked" design similar to that used in the NEDO program. A composite, rather than a steel, flywheel is planned with a diameter of approximately 80 cm. Large, above-ground installation with appropriate protection, is favored over below-ground excavation, due to the projected lower installation expense. It is expected that large energy delivery at > 20 MW would most likely experience some problems with respect to heating of the motor/generator. Flywheels appear attractive also for railway application combined with regenerative braking for charging. Siemens is also conducting studies using flywheels for spinning reserve.

FAULT-CURRENT LIMITERS (FCL)[1]

Summary

Fault-current limiters using high temperature superconductors offer a solution to controlling fault-current levels on utility distribution and transmission networks. These fault-current limiters, unlike reactors or high-impedance transformers, will limit fault currents without adding impedance to the circuit during normal operation. Development of superconducting fault-current limiters is being pursued by several utilities and electrical manufacturers around the world, and commercial equipment is expected to be available by the turn of the century.

Fault-Current Problem

Electric power system designers often face fault-current problems when expanding existing buses. Larger transformers result in higher fault-duty levels, forcing the replacement of existing buswork and switchgear not

---

[1] The general description of fault-current limiters (pages 45-49) that precedes the country-by-country program discussion is adapted, with permission, from an in-house tutorial of American Superconductor Corporation (Brockenborough 1996).

rated for the new fault duty. Alternatively, the existing bus can be broken and served by two or more smaller transformers. Another alternative is use of a single, large, high-impedance transformer, resulting in degraded voltage regulation for all the customers on the bus. The classic tradeoff between fault control, bus capacity, and system stiffness has persisted for decades.

Other common system changes can result in a fault control problem:

- in some areas, such as the United States, additional generation from cogenerators and independent power producers (IPPs) raises the fault duty throughout a system
- older but still operational equipment gradually becomes underrated through system growth; some equipment, such as transformers in underground vaults or cables, can be very expensive to replace
- customers request parallel services that enhance the reliability of their supply but raise the fault duty

Superconductive FCL

Superconductors offer a way to break through system design constraints by presenting an impedance to the electrical system that varies depending on operating conditions. Superconducting fault-current limiters normally operate with low impedance and are "invisible" components in the electrical system. In the event of a fault, the limiter inserts impedance into the circuit and limits the fault current. With current limiters, the utility can provide a low-impedance, stiff system with a low fault-current level, as Fig. 4.5 shows.

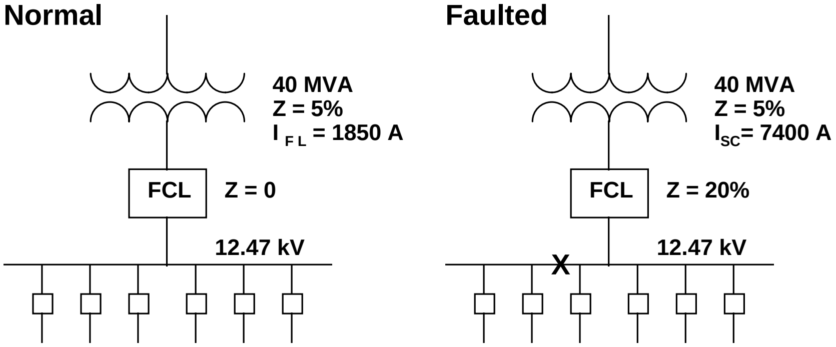


Fig. 4.5. Fault control with a fault-current limiter.

In Fig. 4.5, a large, low-impedance transformer is used to feed a bus. Normally, the FCL does not affect the circuit. In the event of a fault, the limiter develops an impedance of 0.2 per unit (Z = 20%), and the fault current I_{SC} is reduced to 7,400 A. Without the limiter, the fault current would be 37,000 A.

The development of high temperature superconductors (HTS) enables the development of economical fault-current limiters. Superconducting fault-current limiters were first studied over twenty years ago. The earliest designs used low temperature superconductors (LTS), materials that lose all resistance at temperatures a few degrees above absolute zero. LTS materials are generally cooled with liquid helium, a substance both expensive and difficult to handle. The discovery in 1986 of high temperature superconductors, which operate at higher temperatures and can be cooled by relatively inexpensive liquid nitrogen, renewed interest in superconducting fault-current limiters.

Fault-Current Limiter Applications

Fault-current limiters can be applied in a number of distribution or transmission areas. Three main applications areas are shown in Figs. 4.6, 4.7, and 4.8.

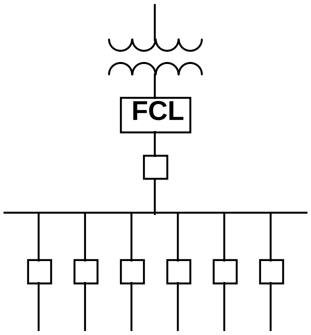


Fig. 4.6. Fault-current limiter in the main position. The fault-current limiter FCL protects the entire bus.

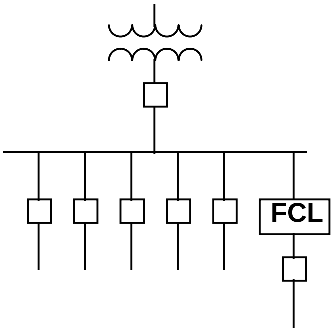


Fig. 4.7. Fault-current limiter in the feeder position. The fault-current limiter FCL protects an individual circuit on the bus. Underrated equipment can be selectively protected as needed in this manner.

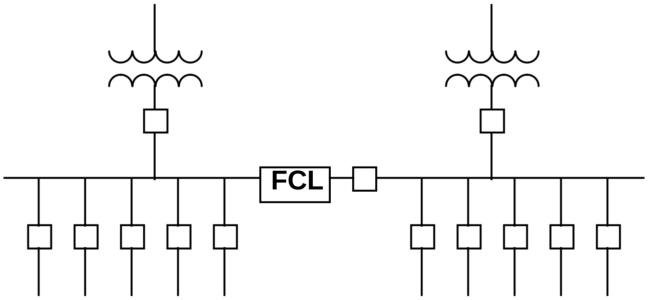


Fig. 4.8. Fault-current limiter in the bus-tie position. The two buses are tied, yet a faulted bus receives the full fault current of only one transformer.

The most direct application of a fault-current limiter is in the main position on a bus (Fig. 4.6). Benefits of an FCL in this application include the following:

- a larger transformer can be used to meet increased demand on a bus without breaker upgrades
- a large, low impedance transformer can be used to maintain voltage regulation at the new power level
- I^2t damage to the transformer is limited
- reduced fault-current flows in the high-voltage circuit that feeds the transformer, which minimizes the voltage dip on the upstream high-voltage bus during a fault on the medium-voltage bus

An FCL can also be used to protect individual loads on the bus (Fig. 4.7). The selective application of small and less expensive limiters can be used to protect old or overstressed equipment that is difficult to replace, such as underground cables or transformers in vaults.

An FCL can be used in the bus-tie position (Fig. 4.8). Such a limiter would require only a small load current rating but would deliver the following benefits:

- separate buses can be tied together without a large increase in the fault duty on either bus
- during a fault, a large voltage drop across the limiter maintains voltage level on the unfaulted bus
- the paralleled transformers result in low system impedance and good voltage regulation; tap-changing transformers can be avoided
- excess capacity of each bus is available to both buses, thus making better use of the transformer rating

Superconductive Fault-Current Limiter Concepts

The Series Resistive Limiter

The simplest superconducting limiter concept, the series resistive limiter, exploits the nonlinear resistance of superconductors in a direct way. A superconductor is inserted in the circuit. For a full-load current of I_{FL}, the superconductor would be designed to have a critical current of $2I_{FL}$ or $3I_{FL}$. During a fault, the fault current pushes the superconductor into a resistive state and resistance R appears in the circuit.

The superconductor in its resistive state can also be used as a trigger coil, pushing the bulk of the fault current through a resistor or inductor. The advantage of this configuration, shown in Fig. 4.9, is that it limits the energy that must be absorbed by the superconductor.

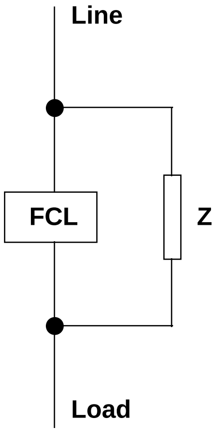


Fig. 4.9. Fault-current limiter with HTS trigger coil.

The fault-current limiter FCL normally is a short across the copper inductive or resistive element Z. During a fault, the resistance developed in the limiter shunts the current through Z, which absorbs most of the fault energy.

The trigger coil approach is appropriate for transmission line applications, where tens of megawatt-seconds would be absorbed in a series resistive limiter. The trigger coil configuration also allows an impedance of any phase angle, from purely resistive to almost purely inductive, to be inserted in the line.

The Inductive Limiter

Another concept uses a resistive limiter on a transformer secondary, with the primary in series in the circuit. This concept, illustrated in Fig. 4.10, yields a limiter suitable for high-current circuits (I_L > 1000 A). One phase of the limiter is shown. A copper winding W_{Cu} is inserted in the circuit and is coupled to an HTS winding W_{HTS}. During normal operation, a zero impedance is reflected to the primary. Resistance developed in the HTS winding during a fault is reflected to the primary and limits the fault.

The inductive limiter can be modeled as a transformer. The impedance of this limiter in the steady state is nearly zero, since the zero impedance of the secondary (HTS) winding is reflected to the primary. In the event of a fault, the large current in the circuit induces a large current in the secondary and the winding loses superconductivity. The resistance in the secondary is reflected into the circuit and limits the fault.

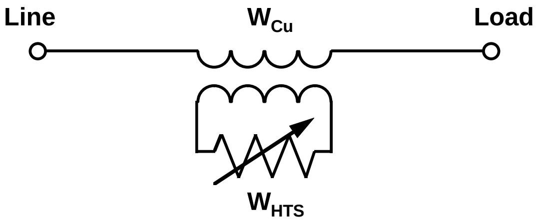


Fig. 4.10. Inductive fault-current limiter.

Japanese FCL Program

The driving factors for current limiters in Japan are somewhat different from those in the United States, given that IPPs and cogenerators are not as prevalent in Japan. Rather, the demand for power in Japanese metropolitan areas continues to grow because of economic growth and increased consumer use of electricity. In addition, industrial use of computers and other power-quality-sensitive equipment has forced the utilities to provide higher quality and more reliable power. The quite successful approach to improved power quality in Japan has been to increase connections between various power systems and to concentrate generation capacity in larger, more efficient units. Increasing interconnection does, however, increase the maximum fault current available at any point in the system, and this is rapidly leading to the need for breaker upgrades and system reconfigurations. Adding to the complexity of the situation in Japan is the limited room at substation sites, which can preclude breaker upgrades. The primary need, as expressed by management of the Tokyo Electric Power Company (TEPCO), is for a limiter for the nucleus of the Japanese transmission system, the 500 kV transmission grid.

In response to this real market pull there has been a series of programs to develop fault-current limiters using a variety of methods, with recent focus on superconducting limiters (Nakade 1994). Although FCLs are not a component of the NEDO budget, TEPCO has reported that it spends about ¥100 million per year (~$1 million) on this program, and some resistive FCL work is apparently included in the NEDO budget under the topic “Research of Superconducting Materials and Devices.”

In the late 1980s, Seikei University manufactured a small-scale three-phase current-limiting reactor and demonstrated successful operation. This three-phase system introduces a large unbalanced reactance in the system to limit currents in the case of a single-phase short and quenches to introduce resistance in the circuit in the case of a three-phase fault.

Mitsubishi Electric Company (MELCO) has been participating in a MITI/NEDO FCL program since 1990. This is a resistive limiter approach using HTS films on a strontium titanate substrate that has demonstrated limiting of 400 A currents to 11.3 A.

The Central Research Institute of the Electric Power Industry (CRIEPI) has developed the inductive limiter shown in Fig. 4.11 (Ichikawa and Okazaki 1995). This approach, similar to those of ABB and Siemens-Hydro Quebec, uses a cylinder of bulk BSCCO-2212 or BSCCO-2223 to separate a normal copper coil from an iron core. In normal operation, the field from the copper coil does not penetrate the superconductor; under fault conditions, however, the current induced in the superconductor is sufficient to drive it normal, and the magnetic field links the iron yoke. This greatly increases the inductance of the copper coil, thus providing current limiting. CRIEPI work has focused on ac magnetic shielding performance of bulk superconductors and their responses to fault currents. In addition, introduction of a “control ring” in the system to absorb some of the energy deposited during a fault has reduced the cooldown time of the shield following a faulted state.

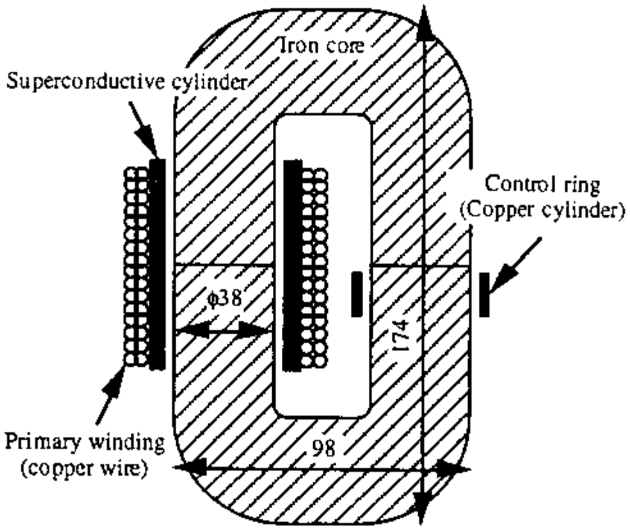


Fig. 4.11. Schematic diagram of the CRIEPI inductive FCL (Ichikawa and Okazaki 1995).

The most extensive FCL program in Japan has been the collaboration between TEPCO and Toshiba. The long-term goal of this program is the development of a 500 kV limiter with a rated current of 8,000 A. Initial development has been focused on a distribution-level limiter designed for 6.6 kV.

As shown in Fig. 4.12, the FCL is formed by connecting four superconducting coils in a series-parallel configuration so the total inductance is minimized. One set of coils is used for each phase of the device, and limiting is accomplished by quenching the coils. The current version of the FCL shown in Fig. 4.13 uses a special low ac loss Nb-Ti conductor. Tests in a circuit with a nominal short circuit current of 25.8 kA have successfully demonstrated limiting to about 4,000 amps (Fig. 4.14).

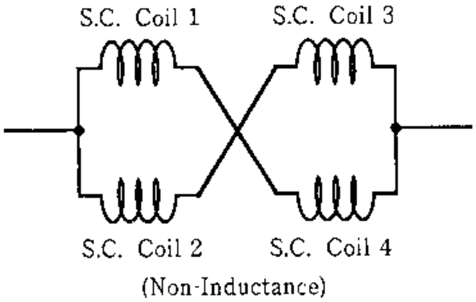


Fig. 4.12. Configuration of coils in the TEPCO/Toshiba FCL (Nakade 1994, 34).

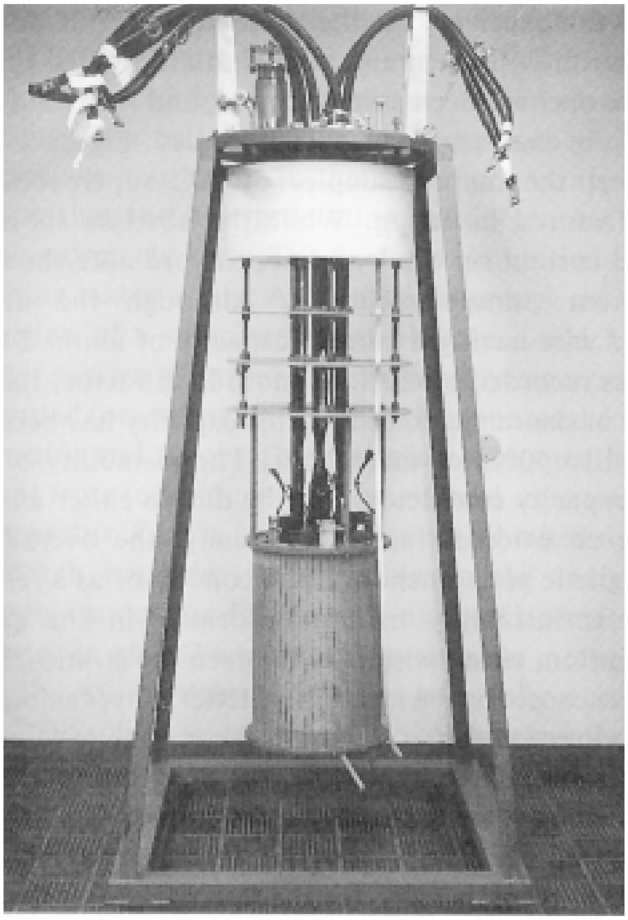


Fig. 4.13. Exterior view of the 6.6 kV 2,000 A-class current limiter. The coil is 420 mm in diameter and 640 mm long (Nakade 1994, 35).

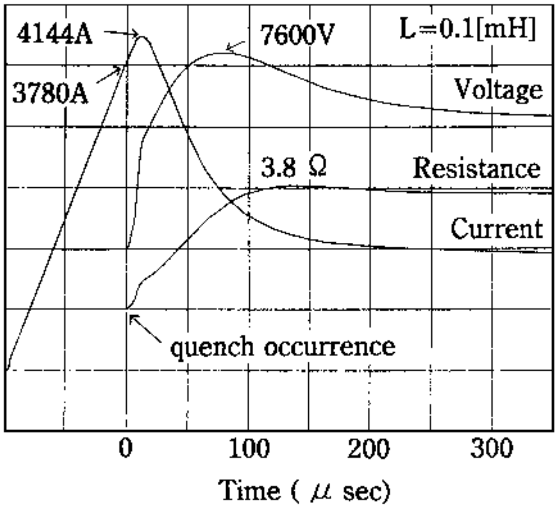


Fig. 4.14. Current limiting characteristics of Toshiba FCL shown in Fig. 4.13 (Nakade 1994, 35).

Recent work has included the introduction of HTS current leads to reduce the refrigeration load of the system to levels that can be handled by a 4 K Gifford McMahon refrigerator. Over three generations of the device, the heat leak has been reduced from 13.8 watts to 3.4 watts, which is nearing the required level.

Future Plans

TEPCO will develop a three-phase limiter over the next three to four years and test it in the grid within this century. There are few distribution-level FCL applications seen in the TEPCO grid, however, and the current plan is to introduce solid state breakers for distribution before installing superconductive FCL.

The true application for the superconducting FCL is at transmission voltages of 500 kV. The view of TEPCO researchers is that this voltage range will require the introduction of HTS coils (rather than LTS) to eliminate the helium gas from the system. Introduction of a transmission-level FCL on the grid is anticipated about 2010.

Fault-Current Limiters In Europe

By far the most comprehensive FCL program in Europe is that being conducted by a collaboration between Electricité de France, GEC Alsthom, and Alcatel Alsthom Recherche. The program's main goal is to provide FCLs for the 225 kV grid in France. The group has chosen a resistive limiter based on LTS material and has demonstrated effective operation at 40 kV (rms), with an industrial demonstration on the French 63 kV grid expected in 1998. Evaluation of the French program is beyond the scope of this WTEC study, so no visit was made to this project. Verhaege et al. (1996) provide an overview of the technology and project status.

Swiss and German FCL Programs

Two sites the WTEC panel visited in Europe addressed FCL: ABB in Baden-Daetwil, Switzerland, and Siemens in Erlangen, Germany. ABB is pursuing a fault-current limiter concept very similar to that described above for the CRIEPI program. It is referred to as the "shielded iron core concept." It uses a warm iron core enclosed by a superconducting shield in a fiberglass Dewar. The copper primary coil is wound external to this Dewar. ABB has constructed and tested a 100 kW prototype using a stack of four Bi-2212 rings 8 cm long, and 20 cm in diameter. Operation was at 480 V with fault currents of 8 kA. A new ABB three-phase 1.2 MW FCL is now in operation in a power station in Löntsch, Switzerland.

Siemens is following two routes for FCL in a collaborative program with Hydro-Quebec Canada. At the Siemens corporate labs in Erlangen, the focus has been on resistive limiters using YBCO thin film meander lines on YSZ or on YSZ and sapphire (Gromoll et al. 1996). The advantage of this approach is that the YBCO film has a high normal state resistance and is not shunted by normal metal, as would be the case in a composite powder-in-tube conductor. The film also has very low heat capacity, which leads to rapid switching to the normal state (< 1 ms) and the possibility of rapid cooldown. Analysis as of 1996 has determined that both peak let-through current and steady state limiting current decrease as J_c is raised. In addition, the design of a limiter of usable size depends strongly on J_c — higher J_c enables a more compact design. The major focus of the program has, therefore, been the fabrication of uniform high-J_c films of YBCO. Techniques investigated have included pulsed laser deposition (PLD), thermal coevaporation, and magnetron sputtering on buffered p-YSZ, unbuffered p-YSZ, and sapphire. Biaxially textured YSZ buffer layers have been fabricated on part of the p-YSZ substrates by ion beam assisted deposition. Current densities up to $3x10^6$ A/cm^2 have been achieved, as have good limiting performance and recovery times on the order of 1 second. The next milestone for the project is construction of a 100 kVA limiter using a cryocooler. Further details of this program are given in the Siemens site visit report (Appendix D).

Two additional German FCL projects began in January 1997. The first is a system study that will be followed by construction of a demonstration FCL. This project is a joint effort by the German utilities RWE, VEW, and Badenwerk, and by EUS GmbH and FZK. The second project involving the development of a small inductive limiter is under the auspices of the German Israel Foundation. The German participants are FZK, Hoechst AG, and the utility Badenwerk; the Israeli participants are Tel Aviv and Ben Gurion Universities.

The work at Hydro-Quebec has resulted in the construction and test of a number of devices since 1992 (Fig. 4.15). The latest system operated at 450 V and 95 amps for a nominal power of 43 kVA. Two different materials were evaluated for the superconducting shield: melt-cast Bi-2212 from Hoechst, and composite reaction textured (CRT) material from Cambridge. Although successful current limiting was demonstrated, the limiter that used the Hoechst material failed during a 480 V short-circuit test due to a fracture of the superconductor (Cave et al. 1996). Subsequent analysis by Hydro-Quebec indicated that thermal stress in the bulk superconductor gave rise to the failure. The near-term future direction of this program will be concerned with improving the homogeneity, critical current density, and resistivity of the bulk superconductor.

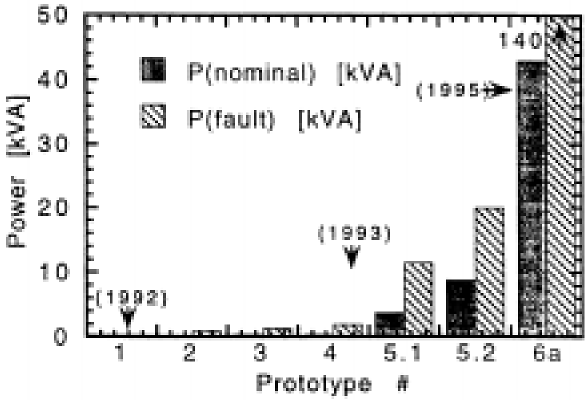


Fig. 4.15. Power rating of the inductive limiter models built/tested at Hydro-Quebec 1992-95 (Cave et al. 1996).

HTS LEADS

HTS current leads represent the first large-scale application of high temperature superconductivity. This has occurred because even modest current density HTS material can be used to provide a significant reduction in the parasitic heat conducted into a cryogenic environment via the electrical leads used to provide current to the device. Fig. 4.16 illustrates a typical application.

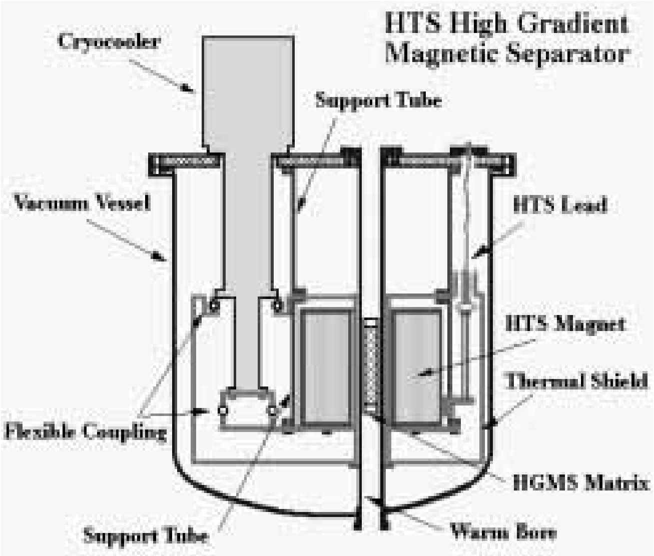


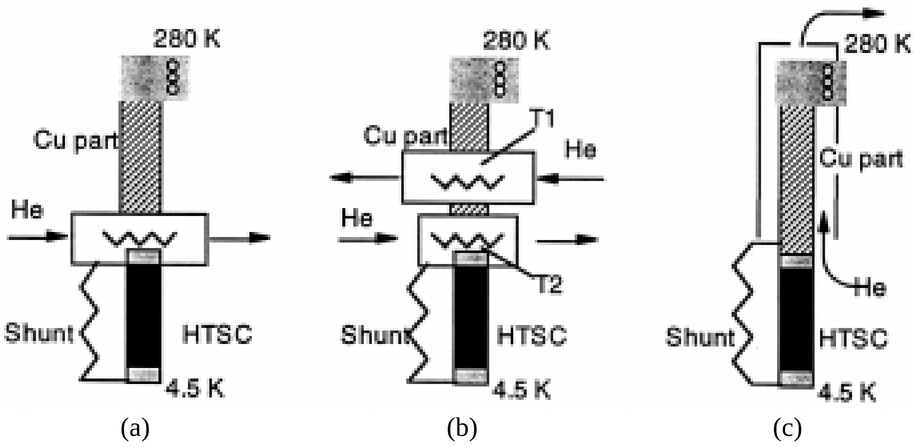
Fig. 4.16. A conduction-cooled HTS magnet system used for magnetic separation, illustrating the use of HTS current leads to reduce heat load (LANL).

There are three classes of applications where HTS leads are seeing rapid introduction:

1. high current LTS magnets cooled by liquid helium
2. conduction-cooled LTS magnets
3. conduction-cooled HTS magnets

High Current LTS Magnets

The application where HTS leads bring the largest financial benefit is large, high current LTS magnets cooled by liquid helium. Examples include accelerator and detector magnets for high energy physics, SMES, and rotating machinery such as the Super-GM generator. These systems all require the transmission of large amounts of current between room temperature and approximately 4 K. In addition, the cryogenic systems on these devices have often been optimized to the point where the leads are the dominant heat load, hence the dominant source of operational cost, of the entire device. If HTS current leads are introduced into the system, the heat leak from room temperature can be intercepted at a much higher temperature (usually 60-77 K) rather than having to be removed at 4 K. Various ways of accomplishing this are illustrated in Fig. 4.17, which is taken from a paper by the CERN Large Hadron Collider (LHC) design team (Ballarino et al. 1996). Method "a" removes the heat with a 50-75 K helium gas stream used to cool the magnet shields. Method "b" uses two gas streams to lower the temperature of the warm end of the HTS lead to 50-60 K. This allows the use of a Bi-2212 lead at the cost of some system complexity. Method "c" uses a stream of helium gas to directly cool the copper portion of the lead. This results in better utilization of the enthalpy of the helium gas, again at the cost of some design complexity. The major point is that, independent of the cooling method, the total refrigeration load with the HTS leads is only a fraction of that in a purely conventional system. As will be reviewed below, these compelling economic advantages have led to the incorporation of HTS leads in, and often to HTS lead development in, almost all new programs involving large LTS devices.



(a) (b) (c)

Fig. 4.17. Suggested methods for cooling the 12.5 kA lead assemblies on the CERN Large Hadron Collider (Ballarino et al. 1996).

Conduction-Cooled LTS Magnets

As will be discussed later in this chapter, the simultaneous development of HTS leads and of Gifford McMahon (GM) refrigerators with capacities over 1 watt at 4.5 K has made possible the introduction of an entirely new class of superconducting magnet, the cryogen-free conduction-cooled magnet. Without the reduction in heat load offered by HTS leads, the realization of these systems would be much more difficult and, in fact, impossible in many cases.

Conduction-Cooled HTS Magnets

The “next turn of the crank” in superconducting magnet technology is the conduction-cooled HTS magnet, discussed in more detail later. In this case, the magnet would be possible even without HTS leads, but the economics of operation is greatly enhanced via the use of the leads, and every HTS magnet shipped to date has used them in some part of the system.

HTS Lead Technologies

There are two basic technologies for HTS leads: bulk rods of ceramic superconductor, and metal matrix superconducting composites. Both have developed to the point that they are offered for commercial sale. There are advantages and disadvantages to each.

Bulk ceramic leads (Fig. 4.18) are made by a variety of methods and of a number of different HTS materials, but the primary objectives are the same: to achieve a rugged ceramic structure with high critical current and low-resistance connections. The advantage of this approach is that the ceramics have intrinsically low thermal conductivity, so that leads may be made quite short for easier integration in the system. The disadvantages are that the ceramic rods are susceptible to breakage during installation, during operation, and (like the bulk structures used in fault-current limiters) during temperature excursions caused by driving the lead normal. In addition, it has proven difficult to provide very low resistance connections between the ceramic superconductor and the metallic connections at the ends of the leads. These disadvantages have been mitigated by careful system design in a number of magnets, and successful systems have been built using bulk leads.

Metal matrix composite leads (Fig. 4.19) essentially use the powder-in-tube technology used for BSCCO wire to manufacture a wire or tape incorporating a low thermal conductivity metal or alloy in place of the customary silver matrix. This approach has employed only Bi-2223 superconductor. The advantages of metallic leads are intrinsic ruggedness, high tolerance to thermal excursions, and very low contact resistances. These advantages are to be balanced against the disadvantage of the somewhat higher thermal conductivity of the composite material, which requires that a longer lead assembly be used to achieve heat leaks comparable to bulk leads.

Fig. 4.18. Bulk HTS leads manufactured by Furukawa Electric.

Fig. 4.19. Metal matrix HTS leads manufactured by American Superconductor Corp.

Japanese and German Lead Programs

HTS lead efforts in Japan are usually part of larger efforts directed toward specific applications; hence, it is difficult to determine budgets. It appears, however, that almost all of the parties participating in HTS materials work have developed current leads. In Germany, Hoechst has introduced a commercial line of bulk ceramic leads. Table 4.1 lists participants, materials used, types of lead technology, and applications.

Table 4.1
Manufacturers, Types, and Applications of HTS Leads in Japan and Germany

Manufacturer	Lead Type	Material	Application
Fujikura, Chubu Electric	Bulk	YBCO	Power Cables
Kobe Steel	Bulk	Bi-2223	LTS Magnets
Fuji Electric, Kyushu Electric	Bulk	Bi-2223	SMES
Mitsubishi	Bulk	Bi-2223	LTS Magnets
Toshiba	Bulk	Bi-2212	LTS Magnets
Sumitomo/Super-GM	Bulk	Bi-2212	LTS Magnets
Sumitomo Electric	Metallic	Bi-2223	SMES, SR Ring
Showa Electric Wire and Cable*	Bulk	Bi-2223	LTS Magnets
Hoechst	Bulk	Bi-2212	LTS Magnets

* Hasegawa 1996

Summary

HTS leads are clearly the first real large-scale HTS products. They have been produced by a number of companies worldwide and are available "off the shelf" in both bulk (Hoechst) and metallic (American Superconductor) form for currents up to 1,000 A. Future developments will include the reduction of heat leak as current density in the superconductor increases and the evolution of specialized leads for unique applications such as SMES and the high energy physics magnets.

HTS SUPERCONDUCTING MAGNETS

HTS has played two roles in the development of superconducting magnets. HTS leads have made possible new classes of LTS magnets, and magnets employing HTS material in the windings have come on the market offering unique advantages.

Refrigerated LTS Magnets

HTS leads have served as an enabling technology for two new classes of LTS magnets, the "cryogen-free" conduction-cooled magnet, and the "zero helium consumption" magnet. These systems operate near 4 K yet consume no liquid cryogens. This mode of operation is particularly attractive in the Pacific Rim, where the cost of liquid helium is much higher than in the United States and Europe, and its availability is sometimes questionable. There are also operational advantages to these magnets: there is no need to train personnel in the handling of cryogens, there is no logistical problem associated with ensuring cryogen supply, and there are fewer safety concerns. Reports from Japanese universities where both conventional and cryogen-free superconducting magnets are installed indicate that the cryogen-free systems are much more heavily used.

As noted in the section above on HTS leads, the cryogen-free magnets require both HTS leads and a GM refrigerator capable of cooling the system to 4 K. The range of available refrigerators has limited the physical size of cryogen-free magnets available; at the time of this WTEC study, all fell in the class of research magnets, as opposed to larger MRI or industrial magnets. In Japan, systems are offered for sale by Kobe Steel, Toshiba, and Mitsubishi Electric Company (MELCO).

A “zero helium consumption” magnet more nearly resembles a conventional LTS magnet in that the coil is submerged in a bath of liquid helium. The cryostats on such magnets, however, are carefully designed to reduce heat leak into the system to a level that can be removed by GM refrigerators. The cryostats usually employ HTS current leads to achieve the necessary thermal performance. These systems normally employ two GM refrigerators. One, operating in the 20-50 K range intercepts radiation heat leak and conduction heat leak from the magnet supports, and it provides a high temperature heat station for the HTS leads. A second, lower-capacity refrigerator operating near 4 K is used to reliquefy the remaining helium boiloff. The major application of these systems has been for MRI magnets marketed in the Pacific Rim. Such magnets are made by MELCO for Shimadzu and by General Electric.

Kobe Steel

As reported in the site report (Appendix C), Kobe Steel in its joint venture with Magnex (Japan Magnet Technology) is addressing the broad spectrum of superconducting magnets for nuclear magnetic resonance (NMR), magnetic resonance imaging (MRI), and general research. This business is leveraged off Kobe Steel’s basic strength in the manufacture of LTS conductors for NMR magnets. Fig. 4.20 shows its conduction-cooled magnet offering. This system is differentiated from that of other vendors by its ability to rotate on gimbals to provide both horizontal and vertical access to the room temperature bore. The technical significance of this is that GM refrigerators designed for operation at 4 K can often operate only in the vertical orientation.

Fig. 4.20. Conduction-cooled magnet offered by Kobe Steel, Ltd., and Japan Magnet Technology, Inc.

Toshiba

It appears that conduction-cooled magnets are less a business thrust for Toshiba than simply a logical extension of a very broad program in superconductivity and cryogenics. Toshiba, like Mitsubishi but unlike Kobe Steel, has developed its own 4 K GM refrigerator. With its LTS magnet and conductor experience and its HTS leads program, Toshiba has in-house all the technology needed to produce these systems. Its 1996 brochure lists 5 T and 10 T models (Fig. 4.21 and Table 4.2).

Fig. 4.21. Toshiba cryogen-free magnet.

Table 4.2
Typical Specifications, Toshiba Cryogen-Free Superconducting Magnets

		TM-5	**TM-10**
Composition	1. Magnet with a small cryocooler 2. Compressor for cryocooler		
Magnetic Performance	Central field	5 T	10 T
	Field uniformity	0.06% over 10 mm DSV	0.12% over 10 mm DSV
	Field ramp rate	5 T / 30 min.	10 T / 60 min.
	Fringe field: Axial (5 Gauss line)	≤ 2.7 m	≤ 3.0 m
	Radial	≤ 2.2 m	≤ 2.5 m
	Rated Current	110 A	135 A
	Stored Energy	91 kJ (inductance 15 H)	188 kJ (inductance 20.6 H)
Physical Parameters	Warm bore diameter	ϕ 120 mm	ϕ 50 mm
	Access type	Vertical/horizontal type	Vertical/horizontal type
	Dimensions	ℓ 730 mm x *w* 580 mm x *h* 696 mm	ℓ 700 mm x *w* 470 mm x *h* 702 mm
	Weight	250 kg	300 kg
Material	Inner warm bore	Stainless steel	Stainless steel
Cryocooler	Cryocooler	Two-stage GM cryocooler	
	Compressor	3 ϕ – AC 200 V – 50/60 Hz, 5.9/7.1 kW	
	Compressor cooling water	6 ~ 8 ℓ / min.	
	Compressor size	ℓ 700 mm x *w* 532 mm x *h* 523 mm	
	Compressor weight	125 kg	
Option	Power supply		
Power Supply (for TM-5)	Input power	1 ϕ – AC 200 V – 50/60 Hz – about 4kVA	
	Rated voltage	dc 4 V	
	Rated current	dc 120 A	
	Current stability	0.005% / hr at rated current	
	Cooling method	Air cooling	
	Size	ℓ 362 mm x *w* 482.6 mm x *h* 222.3 mm	
	Weight	53 kg	

Mitsubishi Electric Corporation (MELCO)

MELCO, like Toshiba, has an active program in GM refrigerator development and has applied this to conduction-cooled magnets. It appears to be marketing these magnets less aggressively than Kobe Steel to the retail market but has maintained a credible presence. The corporate literature (Fig. 4.22) features a 6 tesla Nb-Ti system, and during the site visit, the WTEC team was informed that MELCO has developed a klystron focusing magnet that operates at 3.8 K on a refrigerator. MELCO representatives also stated that they see conduction-cooled magnets as one of the fastest growing segments of the superconductivity market.

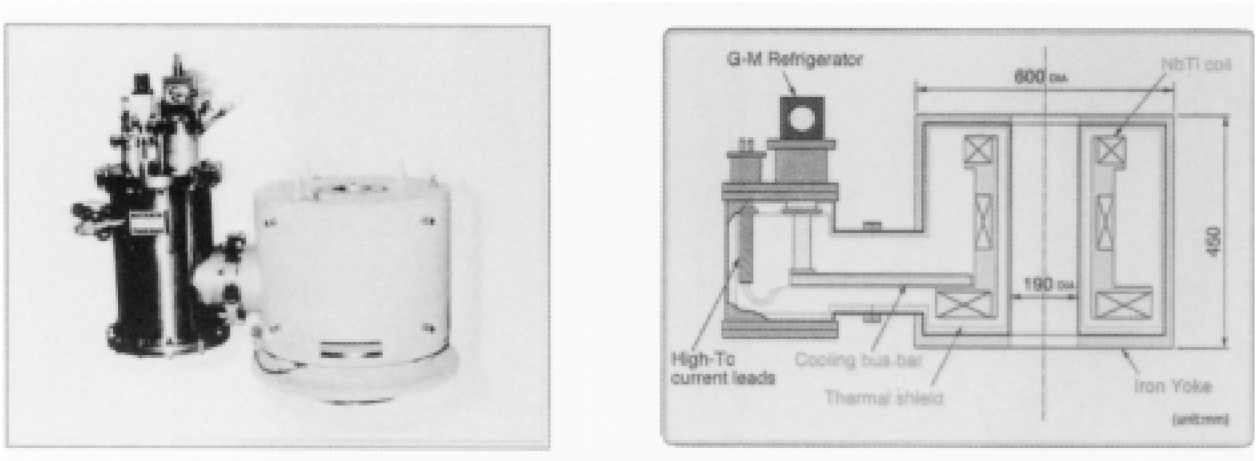


Fig. 4.22. Cryogen-free magnet from Mitsubishi Electric Corporation.

HTS Conduction-Cooled Magnets

While all of the conduction-cooled magnets described above offer the convenience of “dry” operation, they are very limited in the rate at which the magnetic field can be varied. Both the Kobe and Toshiba 10 T systems require one hour to reach rated field. While this is merely an inconvenience for many applications, it does preclude use of the magnets for applications where time-varying fields are required. This limitation, which arises from the fact that significant refrigeration capacity would be required to extract the heat generated in the superconductor, is unlikely to be relaxed in the near future, since 4 K GM refrigerators will always have significantly less cooling capacity than those operating at higher temperatures.

In contrast to the systems described above, Sumitomo has built a series of conduction-cooled all-HTS magnets that operate in the 20-30 K temperature range. These systems offer the advantages of very high operational stability and the ability to ramp very quickly (Fig. 4.23). The disadvantage at the present time is that the higher cost and lower performance of HTS material at 20 K compared to LTS material at 4 K increases the cost and reduces the maximum field of the HTS offerings. It appears that only two firms, Sumitomo in Japan and American Superconductor in the United States, produce cryocooled HTS magnet systems.

High Field NMR Magnets

Nuclear magnetic resonance is a widely used analytical tool in the medical, chemical, and biological industries and is seeing increasing application in industrial process control. NMR’s ability to discriminate between different molecular structures is enhanced by operation at higher frequencies, i.e., at higher magnetic fields. As a result, there has been a steady increase in the operating field of both commercial and research NMR systems, and today commercial systems are available up to 750 MHz. Various vendors are addressing 800 MHz systems, and Oxford Instruments has a contract from the U.S. Department of Energy for the construction of an experimental 900 MHz system. This system is believed to be near the operational limits of doped Nb_3Sn conductor, and it is generally accepted that NMR above 900 MHz (~21.1 tesla) will require the use of HTS insert magnets. HTS conductor has higher current density than Nb_3Sn above about 16 tesla but has not demonstrated the ability to operate in a persistent mode. Several laboratories and companies are attempting to develop persistent mode systems while simultaneously placing into operation nonpersistent research magnets using HTS insert coils.

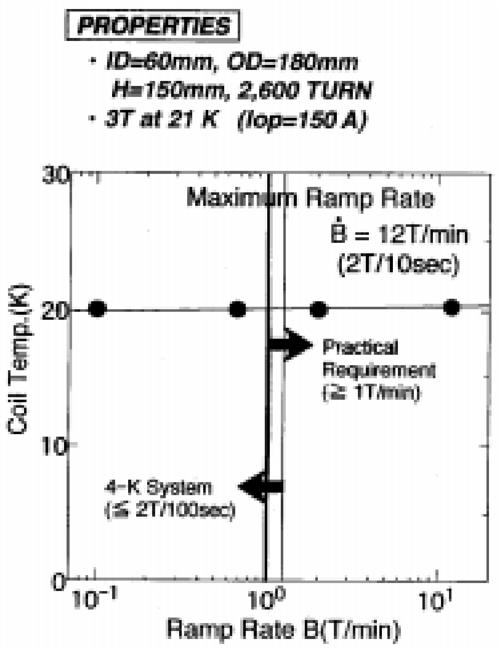


Fig. 4.23. Sumitomo conduction-cooled magnet (Nakahara 1996).

Perhaps the most well-delineated commercial strategy is that of Kobe Steel, which sees market opportunity up to 1.5 GHz for HTS magnets. This is discussed in detail in the Kobe Steel site report (Appendix C). The primary location for the development of high field magnets in Japan is the National Research Institute for Metals (NRIM). This is the site of the multicore program for development of 1 GHz NMR. Japan's Multicore Phase II program provides about ¥170 million per year until 1999 for the 1 GHz NMR project. The emphasis of this program has been on the development of Bi-2212 dip-coated and silver-sheathed tape with high critical current at high field, and on the development of persistent mode operation.

Hitachi Research Laboratory and Hitachi Cable, Ltd., are the collaborators for the silver-sheathed Bi-2212 effort, with measurements being performed at the new Tsukuba Magnet Laboratories of NRIM. The program involves measuring insert coils in the bore of a 21 tesla background magnet. The results shown in Fig. 4.24 indicate the ability to produce conductor J_c approaching 1,000 A/mm^2 and coil current density of ~130 A/mm^2 at 4.2 K in a background field of 21 tesla. According to Okada et al. (1996), these current densities are sufficient to allow fabrication of a 1 GHz NMR magnet.

REFRIGERATORS

Cryogenic refrigeration is a key supporting technology for both LTS and HTS applications. The significant requirements of a cryogenic refrigerator are low cost, reliability, efficiency, and small size.

Large LTS systems, such as high energy physics accelerators and Super-GM generators, use reverse Brayton cycle helium liquefiers. These are complex, expensive systems (the smallest units available cost in excess of $200,000), and are usually specifically designed for each application. Through a number of research projects

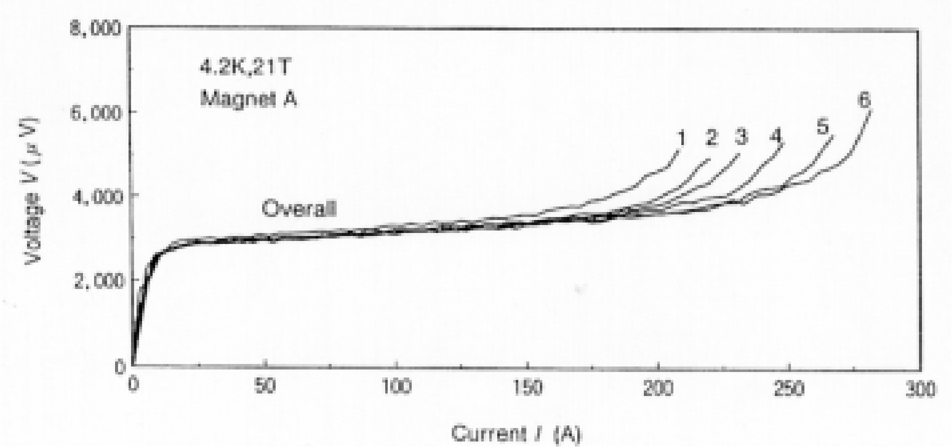


Fig. 4.24. Performance of Hitachi silver-sheathed Bi-2212 multifilamentary conductor (Okada et al. 1996).

conducted over the past 25 years, Japanese industry and particularly the High Energy Physics lab (KEK) have accumulated significant experience with such systems. Components such as compressors and cold boxes are available from a variety of Japanese vendors, and there are several Japanese firms capable of overall system design and integration. In general terms, Japanese technology in this area is very comparable to that available in the United States or in Europe.

Of more relevance to the present topic, however, is the progress in the past several years on smaller Gifford McMahon cycle refrigerators. These systems are widely used in the process industry as a component of vacuum pumps, but only recently have manufacturers begun to optimize their characteristics for use with superconducting magnets. The resulting devices have made possible both the conduction-cooled magnets and the “no refill” MRI systems discussed above.

4 K GM Refrigerators

GM cycle refrigerators employ a regenerator in the coldhead that transfers heat to and from the helium gas working fluid. The regenerator must have very high heat capacity and low thermal conductivity parallel to the direction of gas flow. In the 50-80 K temperature range, single-stage GM refrigerators usually use screens or pellets of copper for the regenerator. Two-stage GM refrigerators designed for use in vacuum pumps operating at 20-25 K use lead in the regenerator because of its higher heat capacity in this temperature range. The lower temperature limit of lead-based regenerators has been about 10 K because of the rapidly declining specific heat of lead below this temperature.

To produce significant refrigeration below 10 K it is necessary to have a regenerator material with a much higher specific heat than lead below 20 K. This is accomplished through use of a material with a magnetic ordering transition and a resulting peak in the specific heat in this temperature range. The materials of choice are the rare earth alloys and compounds. Both Toshiba and Mitsubishi have developed successful regenerator materials. Toshiba has worked primarily with the Er_3Ni system and MELCO with $Ho_{1.5}Er_{1.5}Ru$. Both companies have applied the new refrigerators to conduction-cooled magnets, as noted above. In addition, MELCO has designed a three-stage refrigerator specifically for MRI magnets. This provides cooling at 75 K and 20 K for radiation shields and at 4.2 K for reliquefication of liquid helium. The net result is that MELCO produces an MRI magnet that is initially filled with liquid helium when it is installed but requires no further helium service during its operational lifetime. MELCO has sold over 50 of these magnets to Shimadzu, which has installed them in MRI systems throughout the Pacific Rim. Although not discussed during the site visit (Appendix C), Sumitomo has also developed a successful 4.2 K refrigerator that is now incorporated in “no refill” MRI magnets sold by General Electric in the Pacific Rim.

REFERENCES

Ballarino, A., A. Ijspeert, M. Teng, U. Wagner, S. Harrison, K. Smith, and L. Cowey. 1996. Design of 12.5 kA current leads for the large Hadron collider using high temperature superconductor material. *ICEC*. Japan.

Brockenborough, W. 1996 (February 29). *Medium voltage fault current limiters.* American Superconductor Corporation, Westborough, MA. Duplicated.

Cave, J.R., D.W.A. Willen, R. Nadi, W. Zhu, and Y. Brissette. 1996. Inductive superconducting fault current limiter development. Paper presented at the ICMC in Kitakyushu, Japan.

Furukawa Electric. n.d. *Superconducting technology.* Brochure. Tokyo, Japan: Furukawa Electric.

Gromoll, B., G. Ries, W. Schmidt, H.P. Kramer, P. Kummeth, H.W. Neumuller, and S. Fisher. 1996. Resistive current limiters with YBCO films. Paper presented at the 1996 Applied Superconductivity Conference, Pittsburgh, PA.

Hasegawa, T. 1996. *ISTEC Journal* 9(1):50.

Higasa, H. 1994. *ISTEC Journal* 7(1):43.

Ichikawa, M., and M. Okazaki. 1995. A magnetic shielding type superconducting fault current limiter using a Bi2212 thick film cylinder. *IEEE Trans. Applied Super*. 5:1067.

Nakade, M. 1994. *ISTEC Journal* 7(1):34-5.

Nakahara, T. (Vice Chairman, Sumitomo Electric Industries). 1996 (May 15). ISIS-5 presentation to ISTEC on Sumitomo’s conduction-cooled magnet.

NEDO (New Energy and Industrial Technology Development Organization). n.d. *High-temperature superconducting flywheel energy storage system.* Brochure. Tokyo, Japan: NEDO.

Okada, M., K. Tanaka, K. Fukushima, J. Sato, H. Kitaguchi, H. Kamakura, T. Kiyoshi, K. Inoue, and K. Togano. 1996. *Japan Journal Appl. Phys*. 35(5B):L623.

Verhaege, T., et al. 1996. *Cryogenics*. 36:521-526.

CHAPTER 5

HTS CONDUCTOR TECHNOLOGY

Jeffrey O. Willis

INTRODUCTION

High technology applications are based on the fundamental components from which devices are constructed. For the electronics industry, the fundamental components are the transistor and the integrated circuit, both based on silicon semiconductor technology. For high temperature superconductor (HTS) devices, such as the magnets, generators, and power transmission lines discussed in earlier chapters, the fundamental components are the conductors or wires that carry electrical current in the devices. The steady and significant progress that has been achieved in the field of HTS conductors is highlighted here in terms of the major conductor materials and manufacturing technologies that are being pursued in Japan, Germany, and the United States, along with observations on the sizes and future directions of the conductor programs in these countries.

CONDUCTOR TECHNOLOGIES

Materials

There are several ways to catalog conductor technologies: by material, by application, or by manufacturing technique. The materials method is used here. Four HTS compounds are used for all the large-scale power applications discussed in this report:

1. $(Bi,Pb)_2Sr_2Ca_2Cu_3O_x$ (referred to as Bi-2223)
2. $Bi_2Sr_2CaCu_2O_x$ (referred to as Bi-2212)
3. $(Tl,Pb)(Ba,Sr)_2Ca_2Cu_3O_x$ (referred to as Tl-1223)
4. $YBa_2Cu_3O_x$ (referred to as Y-123 or YBCO)

Tl-1223 may also have some Bi substituted for the Tl or Pb, and the last compound can be formed with many rare earths; in particular, Nd-123 is being exploited as a bulk material for bearings and magnetic levitation.

Manufacturing Technologies

The four major techniques used to manufacture HTS conductors are the (1) powder in tube method, (2) dip coating and other ceramic coating methods, (3) deposition of biaxially textured thin films on textured buffer layers or substrates, and (4) bulk growth techniques.

Sheathed or Powder-in-Tube Conductors

The sheathed, or powder-in-tube (PIT), process was one of the first to be developed for making HTS conductors. The PIT process is now in use in many laboratories and companies around the world. It is sometimes used for Bi-2212 and Tl-1223 and is almost always used for processing Bi-2223 into conductor. Fig. 5.1 shows the steps in the process.

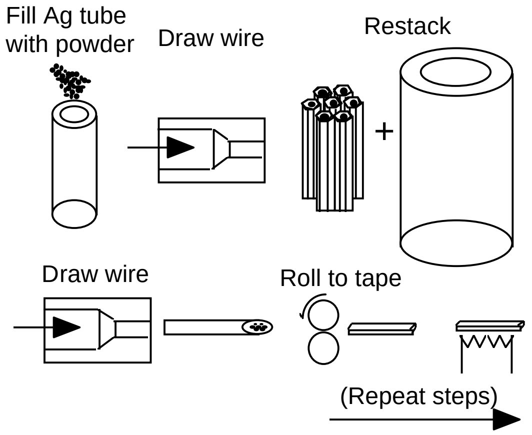


Fig. 5.1. Schematic diagram of the powder in tube process for Bi-2223, Bi-2212, and Tl-1223 wire or tape.

The material of choice for the tube is silver or a silver alloy. Silver is permeable to oxygen, is nonreactive with the HTS core material, lowers the melting point of Bi-based HTS materials during thermal processing, and forms a template upon which the HTS material can grow. Typically, the tube is filled with HTS powder, then extruded or drawn to wire about 1-2 mm in diameter. For multifilament conductor, the wire is drawn in a hexagonal shape, cut into shorter lengths, and formed into a stack of 7, 19, 37, 55, 61, 85, or higher numbers of filaments. This stack is then inserted in another tube, and the composite is extruded or drawn to wire. The restacking and redrawing steps are omitted for monofilament wire. For round wire, the final step is heat treatment, but most conductors are made in a flat "tape" format achieved by rolling the wire to an aspect ratio of ~10:1.

Bi-2212 is subjected to a partial melt process at 800-900°C to form large grains of that compound with the crystallographic a-b planes (i.e., the Cu-O planes that have a high critical current density) oriented parallel to the current flow direction of the tape and to the wide face of the tape. Both Bi-2223 and Bi-2212 are highly anisotropic materials, and the J_c within the a-b plane may be several orders of magnitude larger than J_c along the c axis. Obtaining good uniaxial (c-axis) orientation of the grains in these two materials is necessary to achieve high J_c. Bi-2223 also undergoes a heat treatment (800-840°C) at the tape stage, but then usually goes through one or more additional rolling/heat treatment cycles. Tl-1223 is processed similarly to Bi-2223.

Dip Coating

The second process used for manufacturing superconductors employs typical ceramic techniques such as dip coating or doctor-blade coating of the HTS material (Bi-2212) mixed into a slurry with an organic binder and a solvent onto a substrate, typically silver or silver alloy. Fig. 5.2 shows the process schematically for coating the conductor, coiling into a form, heating to remove the organic materials in the slurry, and then using a partial melt process step to form large-grain, oriented Bi-2212 superconductor. This process has mainly been used to make conductors for magnet applications.

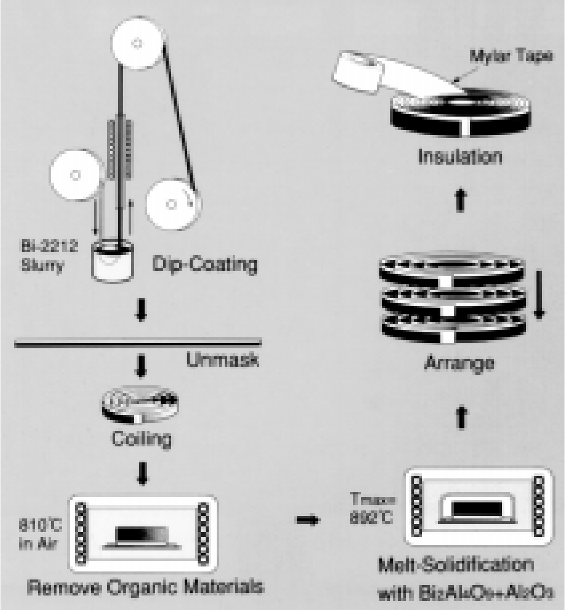


Fig. 5.2. Schematic of typical Bi-2212 coated conductor processing (NRIM 1995).

Biaxially Textured Films

Depositing a superconductor film epitaxially onto a textured buffer layer or textured substrate so as to achieve biaxial texture is the process used to make superconductors of Y-123 and sometimes of Tl-1223. These two materials are more isotropic than the two Bi compounds, and they require both good c-axis grain orientation and also good in-plane orientation. The classic experiment by Dimos et al. (1988) showed that J_c drops by an order of magnitude for current transfer between two grains with parallel c axes, but with the a axis misoriented by only 14°. The best J_c values for Y-123 are obtained for thin films grown epitaxially on single crystal substrates, such as $SrTiO_3$ or $LaAlO_3$, which are impractical for conductors due to high cost, small size, and poor mechanical properties. Instead, Ni, Ni alloys, and Ag are used as substrate materials in one of two processes.

In the first process (Fig 5.3), a buffer layer, of yttrium-stabilized zirconia (YSZ) for example, is deposited on an untextured polycrystalline substrate by one of several techniques to achieve biaxial texture. The Y-123 is then deposited directly on this template or on top of one or more intermediate buffer layers that are grown epitaxially on the YSZ. In the second process, the substrate itself is biaxially textured by thermomechanical processing, typically a very large rolling reduction followed by heating to obtain the preferred grain orientation needed to form a template for the HTS film and any intermediate buffer layers. A protective coating may be made over the HTS film to protect it from the environment and to facilitate attachment of electrical contacts.

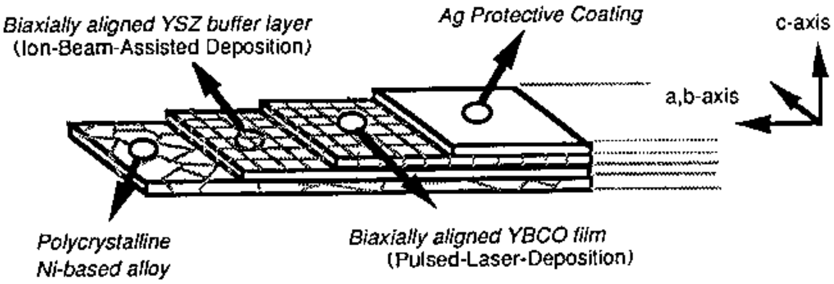


Fig. 5.3. Schematic view of a Y-123 coated conductor (Iijima et al. 1996).

Bulk Processing

The processing of bulk pieces of superconductor makes use of two different techniques. For Bi-2212 and Bi-2223, the HTS material is cast to form a rod or cylinder to be used as a current lead; it then undergoes partial melt processing. The product is not nearly as highly textured as that from the powder-in-tube or dip-coating processes, but since it has a much larger cross-sectional area, it is able to carry a substantial current. There are a variety of related growth techniques for obtaining bulk pieces of Y-123 that rely on one or more thermal gradients to provide large (>1 cm) oriented grains. Seeding with single crystals of Sm-123 has also been effective in nucleating the growth of large Y-123 grains. Various additions, such as Pt and Y_2BaCuO_5 (Y-211), result in enhanced pinning for Y-123. Pieces approximately 10 cm in diameter and 1-2 cm thick can be grown by this technique. Research on rare earth-123 (RE-123) compounds has begun, and now centimeter-size grains of Nd-123 can also be obtained. This material must be grown under controlled low oxygen pressure to prevent site exchange of Nd and Ba that would result in low T_c. Processing to control site exchange and to produce precipitates of $Nd_4Ba_2Cu_2O_x$ (Nd-422) phase yields higher critical current density values at 1-3 T and 77 K than can be achieved with Y-123.

FUNDING AND RESOURCES

Japan

There are three main sources of funding for HTS conductor R&D in Japan: government, electric utilities, and internal funding by companies. The funding levels by the government for the various national projects is a matter of public record, although the fraction of the budgets devoted to HTS conductor R&D are not always clearly delineated. Funding levels of the private electric utilities and the internal funding levels of companies for HTS conductor R&D are not always available, but the latter may be roughly estimated using such indirect indicators as manpower levels and levels needed to match external (i.e., utility or national project) funds.

All national projects related to superconductivity have at least a modest component related to conductor development. The largest source of funds is the Ministry of International Trade and Industry (MITI). This ministry supports some R&D directly, but usually it funds work through the New Energy and Industrial Technology Development Organization (NEDO), a semigovernmental organization that acts as its contracting agency. Major projects supported by MITI include the Flywheel Project, Superconducting Magnetic Energy Storage (SMES) project, Superconductive Generation Equipment and Materials (Super-GM) project, International Superconductivity Technology Center's Superconductivity Research Laboratory (ISTEC SRL), and the Material Manufacture in Microgravity project. The components of each of these five large efforts that are devoted to conductor development vary from a low of 2% for SMES to a high of 10% for ISTEC. The Science and Technology Agency (STA) also supports a large amount of R&D through its Superconducting Materials Multicore Project. This project supports all of the conductor development work at the National Research Institute for Metals and a substantial fraction of that organization's budget. Finally, there is a component of the Ministry of Education (MOE) superconductivity budget that supports HTS conductor development work at the national universities. Table 5.1 summarizes the government share of the HTS conductor development budget.

The second source of funds for HTS conductor development is the electric utility industry. There are only nine utilities in Japan. Most of these companies are members of ISTEC and thus support HTS R&D by both money and manpower. In addition, the three largest utilities, Tokyo Electric Power Company (TEPCO), Kansai Electric Power Company (KEPCO), and Chubu Electric Power Company, directly support HTS R&D in industry. This funding is somewhat analogous to government funding, in that companies typically must cost-share external funding at a 50:50 or higher rate. Company representatives commented to WTEC panelists that outside funds provided from "only a small percentage" to "about half" of a company's total research budget. A good example of this type of funding for HTS conductor development is the support by Chubu Electric of some of the Y-123 coated conductor work at Fujikura.

Table 5.1.
Government Funding Sources for HTS Conductor Development in Japan, FY96

FY96 Project*	Total ($M)	Conductor R&D (%)	Conductor R&D ($M)†
Flywheel	5	5	0.25
SMES	11.5	2	0.23
Super-GM	29	5	1.45
ISTEC SRL	33	10	3.3
Microgravity	26	2	0.52
Multicore (STA)	34.5	25	8.6
University (MOE)	26.5	10	2.65
Total			**17**

* MITI is the source for all projects unless otherwise noted.
† at ¥100 = $1; dollar/yen exchange rate has changed markedly in 1997 (to over ¥120 = $1)

The final source of funds is internal funding by the companies performing the R&D. This takes two forms: (1) internal funding for company projects and (2) internal funding for cost-shared national and utility company projects. An example of the first is Kobe Steel, which supports its conductor R&D for high field NMR insert magnets totally from internal funds; examples of the second are Sumitomo Electric, Toshiba, Mitsubishi Electric, Hitachi, Furukawa, and Fujikura as part of company participation in national projects. Most companies are not willing to discuss their internal budgets for HTS R&D.

Germany

The primary source of government funds for HTS conductor development in Germany is the Ministry of Education, Science, Research, and Technology (BMBF). The BMBF has a superconductivity program with a total annual budget of about $24 million (at DM 1.5 = $1), of which about two-thirds is devoted to power applications. These funds are divided equally between industry (e.g., Siemens) and universities, with an estimated 20% and 40%, respectively, devoted to HTS conductor development. Industry must cost-share its BMBF funding at 50:50. In addition, there is separate BMBF funding to the national laboratories, such as Forschungszentrum Karlsruhe (FZK) and the Max Planck Institutes (MPI), of $4.5 million, about 20% of which is devoted to HTS conductor development. Table 5.2 summarizes the budget for Germany.

Table 5.2.
Funding for HTS Conductor Development in Germany, FY 96

FY96 Funding	Total ($M)	Conductor R&D (%)	Conductor R&D ($M)
BMBF to Industry	11	20	2.2
Industry Cost Share	11	20	2.2
BMBF to Universities	13	40	5.2
BMBF to Natl. Labs.	18	15	2.7
Total			**12.3**

United States

The largest single source of funding in the United States for power applications of HTS in general and HTS conductor development in particular is the Department of Energy's Superconductivity for Electric Systems Program managed by the Office of Energy Management within the Office of Energy Efficiency and Renewable Energy (EERE). Of this $19 million/year program, about half, or $10 million, is devoted to HTS wire development. Much of this funding is provided to the national laboratories, which may subcontract smaller amounts to industry and universities. This program office supports conductor development work in industry directly through a Small Business Innovative Research (SBIR) program. The Office of Basic Energy Sciences also supports (at approximately $1 million) some conductor development work, generally of a more fundamental nature. The National Science Foundation supports conductor development work in universities and through an SBIR program. Some funding is also available to industry through an SBIR program administered by the Department of Commerce. The Department of Defense supports various conductor development efforts in the Air Force, and indirectly through the Navy's motor program. The total estimated U.S. government budget for HTS conductor development is about $13 million/year.

Private industry obtains its funding through several avenues. The main ones are either venture capital, e.g., American Superconductor Corporation (ASC), or internal R&D funds, e.g., Intermagnetics General Corporation (IGC) or Oxford Scientific Technology (OST). In addition, funds may also be received through subcontracts from the national laboratories, from SBIR grants, and from business partners. Budget and manpower figures for conductor development at the companies are largely unavailable. An estimate of conductor development funding is about $1.5 million/year, based on numbers of personnel contributing to journal articles and on estimates of personnel expenses.

The Electric Power Research Institute (EPRI), a consortium of U.S. electric utilities, also funds conductor development at the national laboratories, universities, and in private industry. Some of this support is coordinated with the DOE. Of EPRI's total HTS budget of about $1 million, about one-third, or $0.3 million is devoted to conductor development.

Thus the total estimated U.S. budget for HTS conductor development is about $15 million/year.

PRESENT TECHNICAL STATUS

Performance of HTS conductor materials has been improving continually since the discovery of HTS materials in 1986 and the development of suitable conductor configurations in the following two years. Maeda at NRIM discovered Bi-2212 in 1988; that same year, Vacuumschmelze in Germany developed the oxide powder-in-tube process for Bi-2212. Sumitomo Electric in Japan was one of the earliest organizations to apply this same process to Bi-2223. Many other laboratories around the world began working on these two materials, and in the United States, both ASC and IGC are now producing high quality Bi-2223 conductors for a variety of applications such as motors, magnets, and transmission lines.

Several highlights from the WTEC panel's site visits in Japan and Germany illustrate some of the significant progress in this field.

Bi-2223/Ag Conductors

Bi-2223/Ag-sheath tape has been manufactured by Sumitomo Electric Corporation for a number of years. Sumitomo makes 61-filament Bi-2223/Ag sheath conductors in lengths up to 1,200 m for cable and magnet applications. Now Sumitomo is exploring the use of Ag alloy sheaths for improved performance in high magnetic fields. The main technical issue is that well-annealed Ag, which is the state of the conductor sheath after the final thermal process step, is mechanically very weak, having a low yield stress, and it has a large mechanical mismatch to the Bi-2223 core. To withstand the large Lorentz forces, which produce hoop stresses in a solenoid at high magnetic fields, doped Ag sheaths with higher mechanical strength are desirable. However, this advantage must be balanced against the effect of oxidation of the dopant and possible reaction with the HTS core. Alloys of Ag with Mn, Sb, and Ni have been manufactured, and the mechanical performance has been substantially improved, as can be seen in Fig. 5.4.

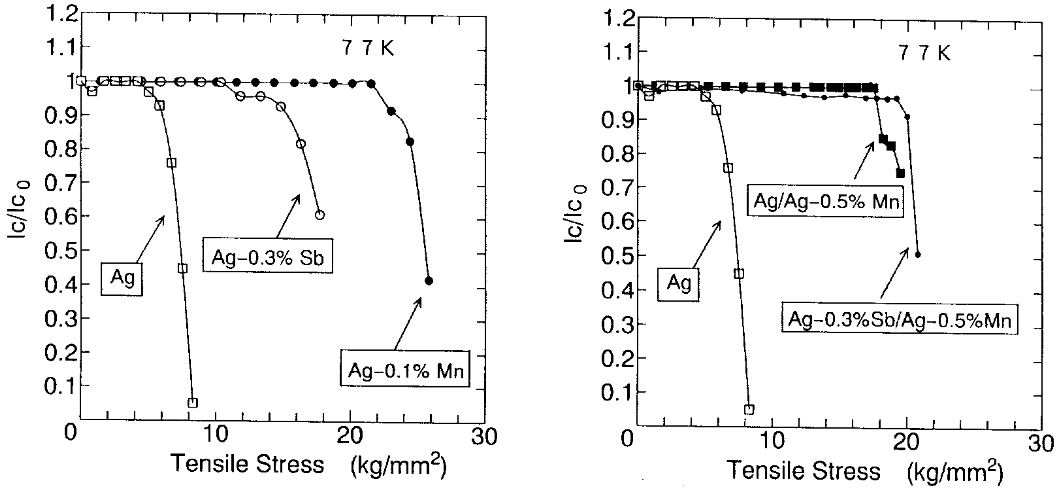


Fig. 5.4 Normalized critical current vs. tensile stress for alloyed sheath tapes. Data on the right is for different outer and inner sheath alloys, as indicated by "inner alloy/outer alloy" compositions for each curve (Hayashi et al. 1996).

Bi-2212/Ag Sheath Conductors

Hitachi Research Laboratory and Hitachi Cable, Ltd., have made major advances within the last several years to produce very high critical current and critical current density Bi-2212/Ag-sheathed tape. This has been achieved by improving the geometric uniformity of the conductor's HTS filaments by a "continuous pressing" deformation process. In this process, multifilament (55) tape is first conventionally drawn to 0.2-2 mm diameter, then it is continuously pressed to a thickness of 0.1-0.2 mm. Finally, it is partially melt processed and then given a final anneal to adjust the oxygen stoichiometry to maximize J_c. Compared with conventionally rolled Bi-2212 multifilament tape, the Hitachi process results in much better geometric uniformity, or much less "sausaging." This improved cross-sectional uniformity results in a higher n value for the current-voltage characteristic ($V = I^n$) and a higher J_c for a long piece length. Conductor performance at 4.2 K is 470 kA/cm^2 at zero field, 171 kA/cm^2 at 30 T parallel to the tape, and 110 kA/cm^2 at 23 T perpendicular to the tape. The data are shown in Fig. 5.5. This wire has been wound into a coil to produce 22.76 T with the aid of a backup field.

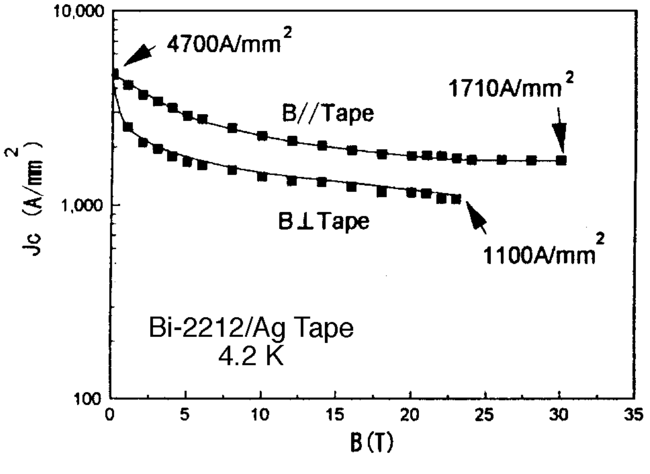


Fig. 5.5. Performance of Hitachi continuous pressed Bi-2212/Ag tape conductor at 4.2 K. The application for this wire is high field insert magnets (1000 A/mm^2 = 100 kA/cm^2) (Okada et al. 1995).

Kobe Steel has also been very active in Bi-2212/Ag sheath conductor development, also with high field NMR (nuclear magnetic resonance) magnets as the target application. Its researchers have investigated two features that they expect to lead to better quality magnets. The first is the use of round wire, rather than flat tape, as the conductor geometry. Round wire has the advantage that it can be wound into a solenoid with very good control over the position of each winding for the generation of a highly homogeneous field. In contrast, flat tape must generally be wound into pancake coils with gaps between the pancakes that generate spatial inhomogeneities. The second feature is the use of alloy sheath materials to improve the mechanical performance of the conductor. In particular, the "double sheath" configuration (Fig. 5.6) for multifilament round wire or tape has several benefits: the outer sheath of Ag alloy with Ni or Mg has high strength, while at the same time the pure Ag inner sheaths eliminate any chemical incompatibilities between the Bi-2212 filaments and the alloying element. The double sheath round wire has been made into a small test solenoid.

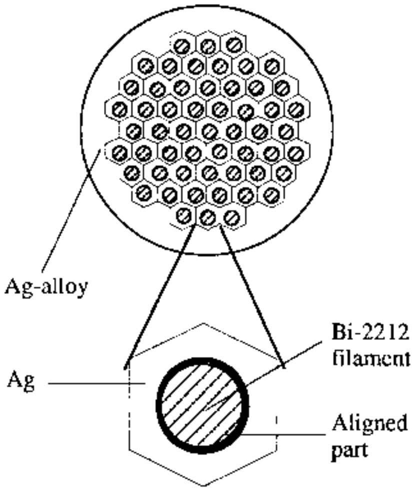


Fig. 5.6. Schematic diagram of a transverse section of a "double sheath" round wire showing the Bi-2212 filament core, the inner Ag sheath, with well textured material at the core/Ag interface, and the outer Ag-alloy sheath for high strength (Hase et al. 1997).

Bi-2212/Ag Coated Conductor

Showa Electric Wire and Cable Company, in collaboration with the National Research Institute for Metals (NRIM), has developed a continuous heat treatment furnace system for processing Bi-2212 coated conductors. In this process, shown schematically in Fig. 5.7, Ag tapes are first coated with a Bi-2212 slurry by dip coating. Three such tapes are stacked and then covered with Ag foil. This composite is then transported through a long oven with an empirically optimized temperature profile. Showa Electric researchers have experimented with many process parameters, including tape speed and reel tension. They have processed up to 100 m lengths at a transport speed of 0.2 m/h to produce a conductor with a J_c of >120 kA/cm^2 at 4.2 K and 12 T with a uniformity of ~20% over the entire length.

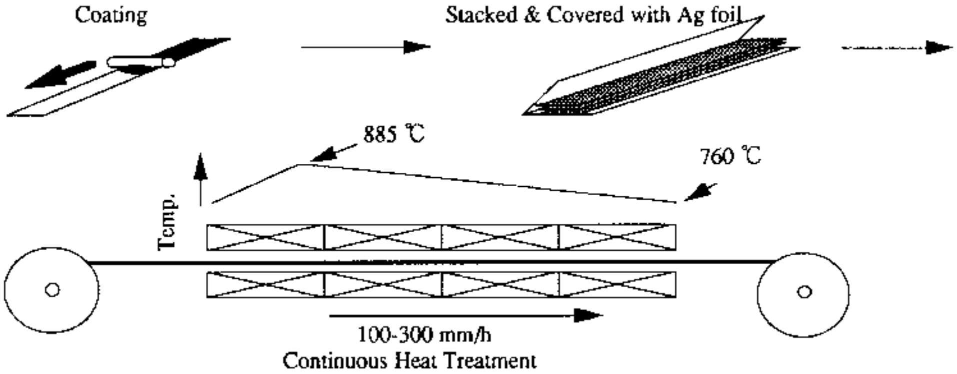


Fig. 5.7. Schematic of the furnace developed by Showa Electric for continuous heat treatment of Bi-2212/Ag coated conductors (Hasegawa et al 1995).

Tl-1223 Coated Conductors

Although many companies, including Hitachi Cable and Sumitomo Electric, have worked with thallium-based HTS materials, for the last several years, except for the interesting fluorine doping work by Tachikawa et al. (1996) at Tokai University, there has been only one strong effort on this material, that based at the Hitachi Research Laboratory. Research there has concentrated on producing Tl-1223 superconductor on thermomechanically textured Ag substrates. In this process, an Ag slab is given a large rolling deformation at a temperature of 130°C. This is followed by a recrystallization heat treatment of 700°C for 1 h and 850°C for 10 h. This results in a highly oriented Ag substrate with good in-plane alignment. Fig. 5.8 shows that the X-ray diffraction phi scan peak width (full width at half maximum, FWHM) is about 6°.

Spray pyrolysis is then used to deposit Tl-0223 precursor directly on the Ag substrate, followed by heating the sample in a Tl-oxide atmosphere to form the Tl-1223 film. The film is c-axis- and mostly in-plane-aligned; however, some grain colonies are oriented at 27° and 45° from the preferred orientation. Fig. 5.9 shows a (103) pole figure of the Tl-1223 film on a {100}<100> textured Ag substrate.

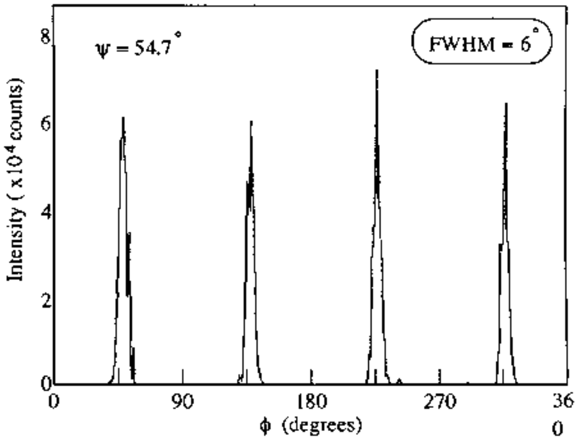


Fig. 5.8. Phi scan of thermomechanically textured Ag substrate (FWHM ~ 6°) (Doi et al. 1996).

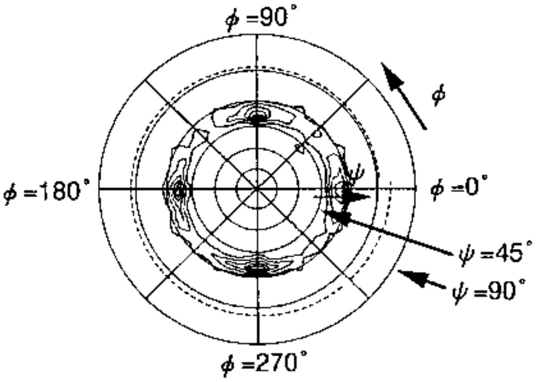


Fig. 5.9. (103) Pole figure of Tl-1223 on the {100}<100> textured Ag substrate (Doi et al. 1996).

The misoriented colonies result in a fraction of the grains being poorly connected (i.e., having weak links) and thus result in degraded critical current density. Nevertheless, comparing the transport properties of these films that have c-axis and partial in-plane alignment with those that have only c-axis alignment (i.e., no in-plane alignment), the transport properties of the former are much better. Figure 5.10 shows that the in-plane aligned sample shows a much smaller decrease in J_c at low field compared to the c-axis aligned sample, indicating a lower level of weak links in the former. The best films grown to date have a J_c at 77 K, 0 T of 100 kA/cm^2 and 15 kA/cm^2 at 1 T B‖c. Hitachi is also examining scale-up processes for longer lengths (~10 m) using multiple spray nozzles.

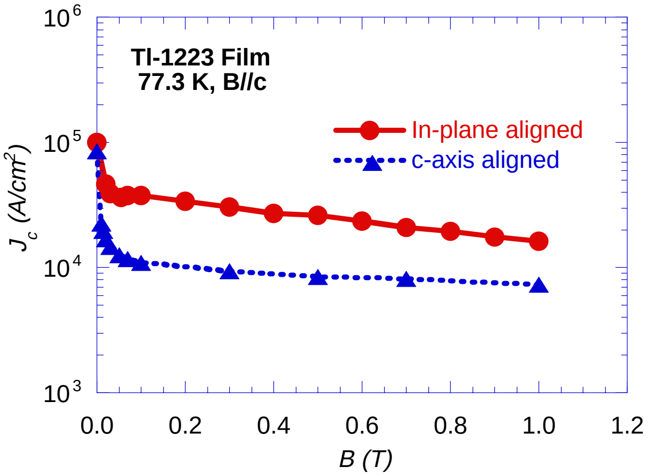


Fig. 5.10. Critical current density of the Tl-1223 film of Fig. 5.9 and a reference film with only c-axis alignment (Doi and Higashiyama 1995).

Y-123 Coated Conductors

Fujikura, Ltd., was one of the pioneers in the development of the Y-123 coated conductor technology. Other organizations in Japan, notably Sumitomo Electric Industries, have been working on developing Y-123 for conductor use almost since the discovery of this material. The major limitation for this material had been the inability to obtain both c-axis and in-plane alignment, which are required to eliminate weak links and obtain high critical current densities, on anything but single-crystal substrates. This problem was overcome by Fujikura, Ltd. in 1992 by the use of ion beam assisted deposition (IBAD) to form a textured buffer layer of YSZ as a template for the Y-123. Polycrystalline nickel alloy (Hastelloy) tape is used as substrate material. The YSZ buffer layer has an in-plane misorientation, characterized by the FWHM of an X-ray diffraction ϕ scan of the (202) peak of 25-30°. The Y-123 film, deposited by pulsed laser deposition (PLD) has an FWHM of the (103) peaks of only 15-20°. This group achieved short sample J_c values of 1.1 MA/cm^2 at 77 K, 0 T in 1995. The sample shows very good in-field performance, as shown in Fig. 5.11.

Fujikura is scaling up its process to longer lengths using IBAD for the YSZ template, but using either PLD or metallorganic chemical vapor deposition (MOCVD) for the Y-123 layer. Fig. 5.12 shows a schematic of the IBAD chamber. Recent results at 77 K and self field for a 0.8 m tape produced by PLD are 0.17 MA/cm^2 (Iijima et al. 1996); under the same measurement conditions, a 0.16 m tape made by MOCVD showed a J_c of 0.21 MA/cm^2 (Onabe et al. 1997).

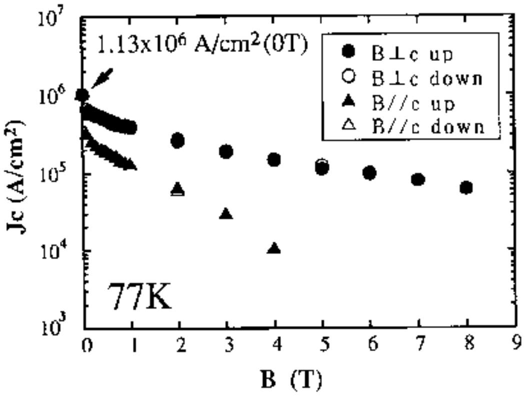


Fig. 5.11. Magnetic field performance of J_c for a high quality Y-123 tape produced by PLD on an IBAD-YSZ buffer on Hastelloy (Iijima et al. 1996).

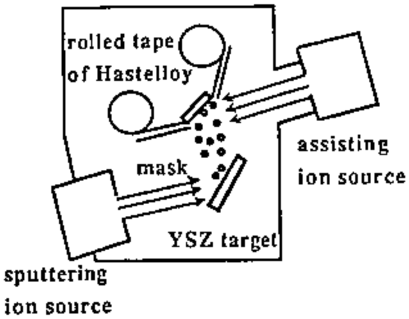


Fig. 5.12. Schematic of IBAD apparatus for deposition on a long length of tape (Iijima et al. 1996).

In May 1996, Sumitomo Electric announced details of a new, non-IBAD technique for producing in-plane aligned YSZ using pulsed laser deposition of the IBAD with the plume directed at an angle to the substrate, as shown in Fig. 5.13 (Hasegawa et al. 1997). This technique has resulted in a YSZ buffer layer with a FWHM of 12.8° when deposited at 0.5 µm/min. In contrast, IBAD buffer layers with FWHM as small as 6° have been reported, but the deposition rate is more than an order of magnitude slower. Sumitomo Electric has produced a tape with 0.5 µm thick YBCO and 0.55 m long with a J_c of 0.2 MA/cm^2 at 77 K, self-field using this technique.

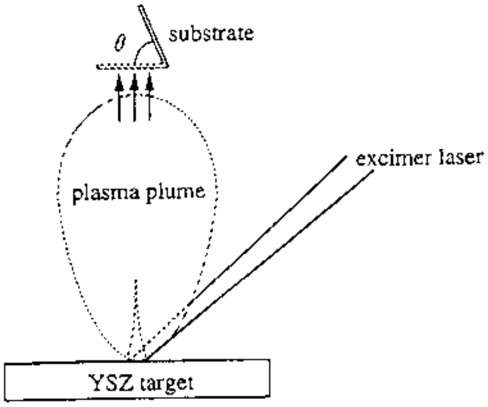


Fig. 5.13. Schematic of the non-IBAD process used by Sumitomo Electric to produce biaxially textured YSZ buffer layers for Y-123 coated conductors (Hasegawa et al. 1997).

M. Fukutomi's group at NRIM is investigating another non-IBAD process for producing a textured buffer layer. This technique makes use of two electrodes installed in a magnetron sputtering system to define the shape of the plasma edge (parabolic) and the direction of the ion flux on the tilted substrate. Fig. 5.14 shows a schematic of the apparatus. The tilted substrate and extra electrodes result in a biaxially aligned YSZ layer.

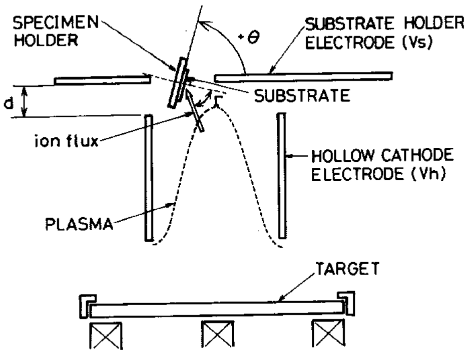


Fig. 5.14. Schematic of the magnetron sputtering apparatus at NRIM with two electrodes to deposit a biaxially textured YSZ buffer layer (Fukutomi, Kumagai, and Maeda 1997).

The two main efforts in Germany are in the groups of H. Kinder at the Technische Universität München and H.C. Freyhardt at the Universität Göttingen. Kinder has been concentrating on producing large-area Y-123 films on single-crystal substrates by thermal evaporation of the three cation constituents from individual boats. The sample is rotated inside a cylindrical box, within which the temperature can be controlled very well and which has a modest oxygen partial pressure for oxidation of the film. A sector of the box is removed to expose the sample to the evaporants. With this apparatus the group has succeeding in fabricating films up to 9 inches (~23 cm) in diameter (Semerand et al. 1997). Freyhardt's group uses IBAD to produce biaxially textured YSZ buffer layers on flat and curved Ni alloy substrates. Large-area (10x10 cm and 20x20 cm) flat surfaces have been coated by rastering and rotating the substrates during both buffer layer and Y-123 film deposition, which is done by PLD. YSZ FWHM values of 10.8° have been achieved on flat substrates; for curved surfaces, the best values are above 20°. J_c values of 1 MA/cm^2 have been achieved for films on small-area flat substrates, and values > 0.1 MA/cm^2 have been achieved on curved substrates and small tubes (15 mm diameter) (Freyhardt 1997).

Bulk Superconductor Components

Bulk current leads are for sale and are supplied in many cryocooled magnets to substantially reduce the heat leak between room temperature and the magnet operating temperature, typically ~10 K, and thus increase the efficiency of the system. These applications are discussed in greater detail in Chapter 4.

Work in Japan on producing bulk Y-123 HTS parts for bearing, levitation, trapped field magnets, and magnetic shielding applications is going on at Nippon Steel, Chubu Electric Power, Fujikura, and ISTEC, among others. Using the quench melt growth (QMG) process Nippon Steel has produced bulk parts and small (12-turn) coils. Chubu Electric is working on bearings, and Fujikura on current leads. ISTEC has the largest effort to produce Y-123 bulk pieces for levitation by the melt powder melt growth (MPMG) technique (Sakai, Yoo, and Murakami 1995). The Y-123 powder contains excess Y that results in Y-211 inclusions during processing, which result in fine precipitates that act as pinning centers and enhance J_c. Small amounts of Pt from the crucible used in the first melt stage help refine the grain size of the Y-211 inclusions. The ISTEC group has produced single disks 8 cm in diameter and 2.5 cm thick that have a repulsive force of 200 N and can levitate 10 kg. A set of 100 smaller-diameter Y-123 pieces assembled on a large plate levitated a 140 kg sumo wrestler and 60 kg support plate to a height of 2.5 cm.

To summarize these highlights and to compare recent results, Tables 5.3 through 5.5 show the state of the art for the different HTS conductor materials and configurations in Japan, Germany, and the United States.

It is clear from these tables that there is rough parity between results achieved in the United States and Japan for Bi-2223 and Bi-2212 conductors, with Germany slightly lagging in production of long lengths. For Tl-1223, the group at Hitachi in Japan is the clear leader. For Y-123 coated conductors, the United States is ahead in J_c and I_c for short lengths, and several Japanese groups lead in the 1 m length category; Germany has good short sample results and has several projects on large area deposition. Japan has the lead in bulk Y-123 and Nd-123, mainly because of the work at ISTEC; the University of Houston also has good results but is concentrating on improving reproducibility in smaller-size disks. Thus, overall, the United States and Japan are producing materials with comparable performance, and Germany is a close third.

CRITICAL ISSUES

Discussions with hosts at the organizations the WTEC panel visited indicate that there is a high degree of consensus on which technical issues are limiting commercial applications of HTS materials and also on some of the approaches to overcome these limitations.

Bi-2223

The main limitation for Bi-2223 PIT conductors is that achievable critical current density is lower than what is needed for applications. That value is widely believed to be 100 kA/cm^2 at 77 K and self field. Solutions to reach this goal include improved powder uniformity and density, better grain alignment, and better thermomechanical process control. The silver sheath widely used also has several drawbacks, such as its poor mechanical strength, which makes handling and Lorentz stresses serious issues, and its low resistivity, which results in extra ac losses. These problems are being attacked by doping the Ag sheath with elements such as Mn to both raise its resistivity and increase its mechanical strength. At least one host cited poor connectivity and low pinning energy as problems, whose solution is to examine other HTS systems.

Bi-2212

For Bi-2212, the problem of low J_c is not considered as serious an issue: operation is typically at 4.2 K, where this material performs better than Bi-2223 and the J_c is already satisfactory. A more severe problem is the lack of uniformity and reproducibility of J_c along the length of a conductor. Here, the solution envisaged is better process control to eliminate second-phase inclusions, which tend to disrupt grain alignment and current flow. The mechanical strength is also too low, especially for the very high field (>20 T) insert magnets manufactured from this conductor. The solution here is similar to that for Bi-2223, i.e., doping the Ag sheath with Mn and other impurities. A “double sheath” arrangement is also of benefit, such that the pure Ag sheath is in direct contact with the HTS material and the more chemically reactive Ag alloy is used as the outer sheath, the alloy material being applied in the restacking operation. A further difficulty with these conductors is the lack of truly superconducting joints and persistent current switches, both important for NMR magnet operation.

Tl-1223

The major issue for Tl-1223 is the less than optimal in-plane alignment of the HTS material on the thermomechanically textured Ag substrate; this limits the performance to about 100 kA/cm^2. Scale-up to long-length production is also an issue, both for deposition of the precursor powder and the thallination, when the Tl vapor pressure and the oxygen pressure must both be controlled.

Table 5.3
Present State of the Art for HTS Conductors — Japan

Material	I_C (A)	J_C (kA/cm^2)	Condition	Length (m)	Organization
Bi-2223/Ag sheath	70	42.5	77 K	0.05	Sumitomo
		27.8		114	
		17.7		1200	
Bi-2212/Ag sheath	500	490	4.2 K, 0 T	~50	Hitachi
		107	4.2 K, 23 T H‖c		
Bi-2212 coated		>170	4.2 K, 0 T	100	Showa Electric/ NRIM
		120	4.2 K, 12 T H‖ab		
Tl-1223 coated	4	100	77 K, 0 T	0.01	Hitachi
		15	77 K, 1 T H‖c		
Y-123 coated		1,100	77 K IBAD/PLD	0.01	Fujikura
	18.1	170	IBAD/PLD	0.8	Fujikura
		200	PLD only	0.55	Sumitomo
Bulk Nd-123		25	77 K, 1 T		ISTEC
Y-123	(200 N)	20		0.08ϕ	ISTEC
		30			Nippon Steel

Table 5.4
Present State of the Art for HTS Conductors — Germany

Material	I_C (A)	J_C (kA/cm^2)	Condition	Length (m)	Organization
Bi-2223/Ag sheath		33	77 K, 0 T	0.02	Vacuumschmelze /Siemens
		22		400	
Bi-2223/Ag sheath		45	77 K, 0 T	short	FZK (Karlsruhe)
		23		long	
YBCO coated		900	77 K, 0 T	0.01	Univ. Göttingen

Table 5.5
Present State of the Art for HTS Conductors — United States

Material	I_C (A)	J_C (kA/cm^2)	Condition	Length (m)	Organization
Bi-2223/Ag sheath (all by rolling)		55	77 K, 0 T	0.05	American Superconductor (ASC)
	34	17.8		280	
		12.7		1160	
	42	21		100	Intermagnetics General (IGC)
		12		1200	
Bi-2212/Ag sheath	225	160	4.2 K, 0 T	>100	IGC
	400	475	(short sample)	200	Oxford
Bi-2212 coated	130	100	4.2 K, 0 T	450	IGC
Tl-1223 coated	18	8	77 K, 0 T	0.02	IGC
Ag sheath	25	20			
Y-123 coated on Ni alloy		600	77 K, 0 T IBAD/PLD	0.001	Lawrence Berkeley National Lab
on Ni alloy	200	1000	IBAD/PLD	0.01	Los Alamos NL
on Ni alloy	13	90	IBAD/PLD	0.07	Los Alamos NL
on Ni	30	700	RABiTS/PLD	0.005	Oak Ridge NL
Bulk Y-123	(30N Lev Force)	(5.5 kG Trapped)	77 K, FC in 1.5 T	0.025 diam	Univ. Houston

Y-123

For Y-123 coated conductors the major issue is the speed of production of the buffer layers and the Y-123 film. For use of ion beam assisted deposition of the biaxially textured (usually YSZ) buffer layer, this is the rate-limiting step. Several non-IBAD processes are being explored to address this issue, such as pulsed laser deposition with an inclined substrate and shaped electrode magnetron sputtering. In long-length scale-up, it will be important to maintain good biaxial alignment of the buffer layer. Other important issues for MOCVD deposition of the Y-123 are thickness and J_c uniformity, reaction layers, oxygen pressure control, and speed.

Bulk Materials

The critical issues for bulk HTS materials, primarily Y-123, are the needs for larger and better aligned grains with improved pinning properties. One or more temperature gradients have been employed to achieve larger, better aligned grains, and doping with excess Y and small amounts of Pt have been used to improve pinning. Work on the RE (Nd or Sm)-123 systems focuses on control of the partial pressure of oxygen to achieve the best superconducting transition temperature and on better understanding of the source of pinning in this material. Currently, better in-field performance can be achieved in the RE-123 materials, but the overall sample size that can be grown is smaller than for Y-123.

FUNDING PROSPECTS

Japan

Because most of Japan’s HTS conductor development program is a tightly integrated part of its overall national program for superconductivity, these comments apply equally to the whole program and to its parts. Government funding for national projects has been very stable for the period 1986 to 1996 and should continue to be stable in the near future. However, there is some uncertainty as of this writing as to what projects might follow Super-GM and as to the nature of Phase II for ISTEC. Industry funding has been cut back from the initial “superconductivity fever” level, which also occurred during a time of great domestic prosperity, to a more sustainable level as Japan begins to emerge from a long and hard recession. At this time, most of the major wire and electrical equipment companies continue to have strong R&D programs in HTS materials development.

Germany

Funding for HTS materials in Germany is centered around the BMBF program (~\$24 million/yr. +\$18 million/yr. for national laboratories), which does an excellent job of integrating industry, university, and national laboratory efforts. The funding levels have stabilized after the major national political and economic changes brought on by reunification with the former East Germany. Like Japan, Germany’s BMBF program supports both low and high T_c R&D. The presence of very strong large magnet fusion programs also helps to provide a firm technology base. At present, the German government views superconducting power devices as precompetitive, and as such, there are good prospects for a second four-year program starting in 1997.

The United States

In the United States, government (primarily DOE) funding levels for HTS conductor development have been fairly steady in the last few years, but they are subject to change on the annual congressional budget cycle. This of course makes long-range planning very difficult. Most of the private companies working on HTS are funded by venture capital; it is also very difficult to have a long-range outlook when business considerations focus on a quarterly time horizon. On the other hand, as a counterpart to this WTEC survey, a 1995 ISTEC survey panel on HTS progress in the United States concluded that the economically motivated short time focus of U.S. venture capital companies is a great advantage compared to the longer time horizons of the large, well-funded companies in Japan, in that innovation and progress tend to occur at a much faster rate.

SUMMARY AND CONCLUSIONS

Comparing progress in HTS conductor development among the three countries, the United States and Japan are very comparable in Bi-2212 and Bi-2223 conductor development, with Germany lagging somewhat in long lengths. Bi-2223 is considered the conductor of choice by many organizations in Japan for most applications for the next five to ten years. Tl-1223 progress is dependent on small efforts in the United States and Japan, and its future seems uncertain. Y-123 coated conductors, on the other hand, are being intensively investigated by two or more groups in each of the three countries. This is a very promising new technology in its early stages, and many production processes are being pursued. Most WTEC hosts in Japan felt that a practical Y-123 coated conductor is at least five years away. The United States is ahead in short length performance but behind in longer length (1 m) scale tape production. Germany is lagging both efforts for conductors, but has some interesting work on large area films. Work on bulk conductors is dominated by strong efforts in Japan at Nippon Steel and ISTEC, but there are considerable progress and innovative applications at the University of Houston in the United States. Thus overall, the United States and Japan are producing materials with comparable performance, and Germany is a close third. Future prospects for improved materials will, of course, depend on the further availability of R&D funds.

Progress in improving HTS materials, and especially materials relevant to power applications, has been steady and continuous since the time of the JTEC study (Dresselhaus 1989) on HTS in Japan. Today, many prototype applications that use HTS materials, such as fault current limiters and transmission lines, are being built in Japan, Germany, and the United States. Progress has been tied directly to funding levels in these countries. In Japan and Germany, progress is strongly coupled to long-term national projects, such as Super-GM, ISTEC, and the BMBF program, and (for Japan) the needs of utilities. The utilities provide both direction and some economic support to HTS wire manufacturers. Clear market potential drives the development of new products in “old” industries looking for new markets, such as the wire and cable and the steel industries. Internal R&D funds in Japan and Germany are steady, and companies still are able to support long-range goals. Finally, the distinction between LTS and HTS conductor development is not as marked as in the United States — they are simply superconductivity development programs. The level and scope of government and privately funded efforts in both Japan and Germany are the result of a clear belief that superconductivity will be an important 21st century technology. The United States must make a similar commitment if it is to maintain its position in the forefront of HTS conductor development.

REFERENCES

Dimos, D., P. Chaudhari, J. Mannhart, F.K. LeGoues. 1988. Orientation dependence of grain-boundary critical currents in $YBa_2Cu_3O_{7-d}$ bicrystals. *Phys. Rev. Lett.* 61:219-222.

Doi, T.J., and K. Higashiyama. 1995. Preparation of thallium-based high-T_c oxide superconducting thick films on textured substrates. *Oyobutsuri* 65:372-376 (in Japanese).

Doi, T.J., N. Sugiyama, T. Yuasa, T. Ozawa, K. Higashiyama, S. Kikuchi, and K. Osamura. 1996. Biaxially oriented Tl-1223 film with high J_c on {100}<001> textured Ag tape. In *Adv. in Superconductivity 8,* 903-906, ed. H. Hayakawa and Y. Enomoto. Tokyo: Springer-Verlag.

Dresselhaus, M., et al. 1989. *High Temperature Superconductivity in Japan.* Baltimore, MD: Loyola College, Japan Technology Evaluation Center (JTEC). NTIS Publication PB90-123126.

Freyhardt, H. 1997. YBCO thin films on tapes and tubes. In *IEEE Trans. Appl. Superconductivity* (in press); Paper MHB-1, Proceedings of the Applied Superconductivity Conference, Pittsburgh, PA, 26-30 Aug. 1996.

Fukutomi, M., S. Kumagai, and H. Maeda. 1997. Fabrication of $YBa_2Cu_3O_y$ thin films on textured buffered layers grown by plasma beam assisted deposition. *Australian J. of Physics* 50:381-389.

Hase, T., K. Shibutani, S. Hayashi, M. Shimada, R. Ogawa, Y. Kawate, T. Kiyoshi, and K. Inoue. 1997. Fabrication of double-sheathed Bi-2212 multifilamentary wire. In *Proc. 16th Int. Cryogenic*

Engineering Conf./Int. Cryogenic Materials Conf., 1409-1412, ed. T. Haruyama, T. Mitsui, and K. Yamafuji. Oxford, UK: Elsevier Science.

Hasegawa, K., N. Yoshida, K. Fujino, H. Mukai, K. Hayashi, K. Sato, T. Ohkuma, S. Honjyo, H. Ishii, and T. Hara. 1997. In-plane aligned YBCO thin film tape fabricated by pulsed laser deposition. In *Proc. 16th Int. Cryogenic Engineering Conf./Int. Cryogenic Materials Conf.*, 1413-1416, ed. T. Haruyama, T. Mitsui, and K. Yamafuji. Oxford, UK: Elsevier Science.

Hasegawa, T., Y. Hikichi, H. Kumakura, H. Kitaguchi, and K. Togano. 1995. Fabrication and superconducting properties of $Bi_2Sr_2CaCu_2O_y$ multilayer tape prepared by a continuous heat treatment. *Jpn. J. Appl. Phys.* 34:L1638-L1640.

Hayashi, K., N. Saga, K. Ohgura, and K. Sato. 1996. Ag alloy sheathed BPSCCO superconducting wires. In *Adv. in Superconductivity 8*, 811-814, ed. H. Hayakawa and Y. Enomoto. Tokyo: Springer-Verlag.

Iijima, Y., M. Hosaka, N. Tanabe, N. Sadakata, T. Saitoh, O. Kohno, and J. Yoshitomi. 1996. Fabrication of high-J_c tapes using continuously deposited YSZ buffer layers by IBAD method. In *Adv. in Superconductivity 8*, 659-662, ed. H. Hayakawa and Y. Enomoto. Tokyo: Springer-Verlag.

NRIM. 1995. *Introduction to National Research Institute for Metals*. Tsukuba, Japan: NRIM.

Okada, M., K. Tanaka, J. Sata, S. Awaji, and K. Watanabe. 1995. Transport properties of $Bi_2Sr_2Ca_1Cu_2O_x$/Ag multifilament tape. *Jpn. J. Appl. Phys.* 34:4770-4773.

Onabe, K., S. Nagaya, T. Shimonosono, Y. Iijima, N. Sadakata, T. Saito, and O. Kohno. 1997. Fabrication of YBCO superconducting tapes by continuous MOCVD technique. In *Proc. 16th Int. Cryogenic Engineering Conf./Int. Cryogenic Materials Conf.*, 1413-1416, ed. T. Haruyama, T. Mitsui, and K. Yamafuji. Oxford, UK: Elsevier Science.

Sakai, N., S.I. Yoo, and M. Murakami. 1995. Control of Y_2BaCuO_5 size and morphology in melt-processed $YBa_2Cu_3O_{7-d}$ superconductor. *J. Mater. Res.* 10:1611-1621.

Semerad, R., P. Berberich, B. Utz, W. Prisseit, and H. Kinder. 1997. Deposition of YBCO films on areas of 9 inches in diameter. In *IEEE Trans. Appl. Superconductivity* (in press); Paper ME-1, Proceedings of the Applied Superconductivity Conference, Pittsburgh, PA, 26-30 Aug. 1996.

Tachikawa, K., A. Kikuchi, T. Kinoshita, T. Nakamura, and S. Komiya. 1996. Critical current in Tl-base high-T_c oxides prepared by a diffusion process. In *Adv. in Superconductivity 8*, 915-918, ed. H. Hayakawa and Y. Enomoto. Tokyo: Springer-Verlag.

CHAPTER 6

LOW T_C SUPERCONDUCTOR R&D IN JAPAN

Masaki Suenaga

INTRODUCTION

Although the major emphasis of this WTEC study is on high T_c superconductors and their applications in the utility systems in Japan, a short report on low T_c superconductor R&D in Japan is included, since a very significant and surprisingly large part of the Japanese R&D on superconductors and their applications is focused on low T_c superconductors, even well after the discovery of high T_c superconductivity. Some developments in Japan that are discussed below are unique for Japan, are new, or are not widely known.

SOURCES AND METHODS OF FUNDING

In general and as seen in Table 6.1, all of Japan's conductor development projects are related to government- or electrical power industry-supported large feasibility test projects such as Super-GM. A part of each project is devoted to development of the conductors required for the project's particular devices. Although each government-sponsored project initiates the development of a particular conductor and pays private manufacturing companies for the development, it is generally thought that the expenses of conductor development are primarily borne by the manufacturing companies. In addition to large-project-related conductor developments, there are a couple of developments internally supported by industry, as shown in Table 6.1. One of these, the development of Nb_3Sn conductors by Kobe Steel, Ltd., appears to have made a significant contribution toward the company's successful commercialization of high field magnets for high frequency (>700 MHz) nuclear magnetic resonance. Due to the high quality of its conductors, i.e., high J_c and a sharp transition in the I-V curves, Kobe Steel appears to be able to compete effectively in a market that has been dominated for a number of years by Oxford Instruments in England.

COMPARISON OF R&D EFFORTS IN JAPAN AND THE UNITED STATES

Table 6.1 compares Japanese and U.S. efforts on development of low T_c superconductors, in terms of approximate levels of relative effort and names the supporting funding agencies. It is clear that Japan dominates the R&D effort in low T_c superconductors; this is due primarily to its government's interests in the use of superconductors in the electrical utility industry and in the development of magnetic fusion power reactors. The one significant area where the United States and Japan are equally competitive is in development of Nb_3Sn conductors for the International Thermonuclear Experimental Reactor (ITER) project and for high energy physics particle accelerators. There is no R&D support in the United States for the development of conductors for electrical power applications at 50-60 Hz or of Nb_3Al conductors for the ITER.

Table 6.1.
Comparison of U.S. and Japanese Efforts in Low T_c Conductor R&D
(Project Sponsors Are Named in Brackets)

Material	United States	Effort	Japan	Effort
NbTi	• Artificial pinning wire (HEP/DOE, SBIR)	Medium	• Artificial pinning wire (Industry)	Small
			• Low ac loss (50-60 Hz) wires (Super-GM/MITI, Power Utilities, MOE)	Large
Nb_3Sn	• High field, high J_c, and low hysteresis loss (OFE/DOE, HEP/DOE, SBIR)	Large	• High field, high J_c, and low hysteresis loss (JAERI/STA)	Large
	• High field, high J_c-NMR (Industry)	Small	• High field J_c - NMR (Industry)	Small
Nb_3Al	• High field J_c (SBIR)	Very Small	• High field J_c and low hysteresis loss (Magnetic Fusion/STA) (NRIM/STA)	Large
Other			• V_3Si (NRIM/STA) • Chevrel (ETL/MITI) • V_2(Hf, Zr) (NRIM/STA)	Very Small

Table 6.2 names the types of conductors that are currently manufactured for various projects in Japan and the manufacturers that are involved in these developments. Particularly notable developments are marked with asterisks. The manufacturing processes and the intended applications for these conductors are discussed below. It is clear from the table that a number of large companies in Japan are involved in R&D of low T_c wire manufacture for various applications, which is not the case in the United States.

Table 6.2
Low T_c Conductors, Applications, and Manufacturers in Japan

Material	Type or Process	Application	Manufacturers
NbTi	• Monoliths	• Magnetic resonance imaging, Maglev, nuclear magnetic resonance (NMR)	Fujikura Furukawa Electric Hitachi Cable Kobe Steel Showa Electric Wire & Cable Sumitomo Electric Industries
	• Stranded cables	• High energy particle accelerators, electric power applications*	
	• Cable in conduit	• SMES	
Nb_3Sn	• Bronze process	• Magnetic fusion/ITER, high field NMR, electric power applications	Fujikura Furukawa Electric Hitachi Cable Kobe Steel Mitsubishi Electric Co. Showa Electric Wire & Cable Sumitomo Electric Industries
	• Internal tin process*	• Magnetic fusion/ITER, electric power applications	

***** Particularly notable developments

LOW T_C CONDUCTOR DEVELOPMENT FOR ELECTRIC UTILITY DEVICES

Super-GM-Supported Conductor Development

The Super-GM project (see also Chapter 2) supports conductor development projects for eventual use in stators of full-sized SC generators, practical reactors (e.g., 66 kV/100 MVA), fault current limiters, etc. Various manufacturers are developing both NbTi and Nb_3Sn wires, as listed above. Figure 6.1 shows a typical cross-section of a conductor and a wire and a schematic for construction of a low ac loss NbTi cable. The cross-section of the basic wire is heavily segmented with a high-resistance NiCu alloy, which occupies approximately 80% of the wire. Most of the remainder is fine filamentary (filament diameter < 0.2 µm) NbTi and a small amount, if any, of Cu (0-3%). All of this is done to reduce the ac losses at power frequencies. The I_c performance of a conductor for armature windings is approximately 3,000 A_{rms} at 1.5 T and 4.2 K. The goal of the project is to produce conductors that can carry an I_c of several kA_{rms} at 1.5 T. This wire development follows earlier projects, which were supported by Japan's Ministry of Education (MOE), on construction of transformers at a number of universities. The largest of these transformers was built at Kyushu University with a design power rating of 1,000 kVA, but the conductor for the transformer was able to carry only 60% of the rated current (4.5 kA_{rms}), although the small-scale test of the conductor met all the design specifications. The source of this degradation of I_c for large conductors is still not known. Thus, the main goal of the Super-GM project for NbTi conductors is to increase the total current capacity under realistic conditions for power device applications.

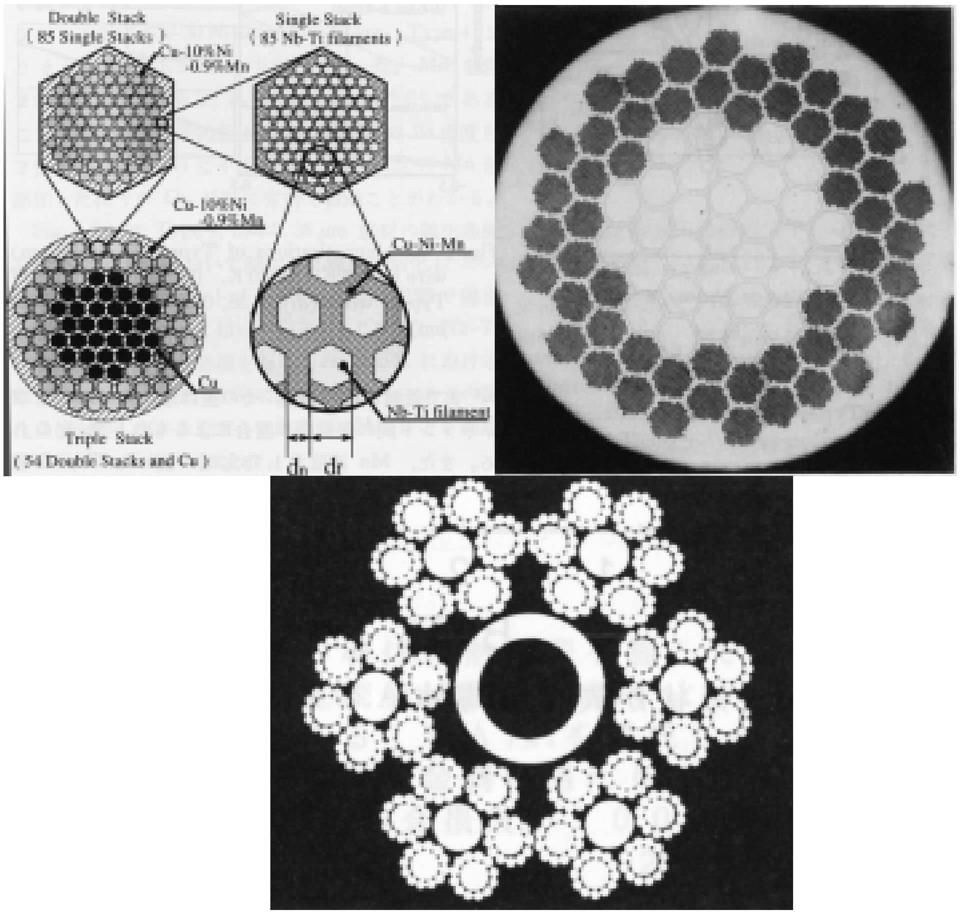


Fig. 6.1. Cross-sectional pictures of typical NbTi wire and cable used for electrical utility devices such as transformers: a schematic diagram for construction of a wire for use at power frequencies (top left), a cross-section of a finished wire (top right), and a third stranded cable (bottom).

The Super-GM project also supports extensive development of ac conductors using Nb_3Sn in order to take advantage of its higher T_c and associated better thermal stability. All of the major manufacturers of superconductors are participating in the project (Table 6.2). In contrast to NbTi wire, Nb_3Sn wire can be fabricated in a number of ways. Although the so-called "bronze" and "internal tin" processes are the most commonly used methods for large-scale production of wire, apparently wires have also satisfactorily been produced by other methods that meet two of the project's preliminary goals: ac loss ≤ 25 kW/m^3, and $I_c > 1$ kA at 0.5 T and 4.2 K. However, final target levels for I_c and ac losses for Nb_3Sn have not been reported.

CRIEPI-Supported Conductor Development

Outside of the Super-GM project, the Central Research Institute for the Electric Power Industry (CRIEPI), in collaboration with Nihon University and Showa Electric Wire and Cable Company, is developing Nb_3Sn wires for ac applications by using a novel approach to the internal tin process. As will be discussed below in connection with conductors for ITER, the effective filament size in the internal tin processed wire is generally much greater than a few micrometers. However, in order to reduce ac losses at power frequencies, the size of the filaments must be well below one micrometer, and this is not usually achieved in the standard high field wires. Part of the reason for this is that the filaments tend to coalesce during high temperature (~ 700°C) heat treatment for forming Nb_3Sn. What the CRIEPI group has found is that for ac applications the heat treatment temperature can be quite low, e.g., 450-500°C, to react all of the Nb filaments to Nb_3Sn, if the filaments are drawn down to submicron (≤ 0.3 μm) dimensions. This low heat treatment temperature can keep the coalescence of the filaments to a minimum, even though the value of T_c (~ 14 K) of the Nb_3Sn produced is substantially lower than what is achieved in a standard heat treatment. Small coils have been made, and they were being tested in mid-1996 for their ac excitation performance.

Electric Utility-Supported Conductor Development

Another source of support for development of low T_c superconductors is the electric power utilities. For example, Tokyo Electric Power Company (TEPCO) has been supporting development of a fault-current limiter with NbTi wire. In this application, ac losses at power frequencies are a primary factor in the design, and the conductor for the fault-current limiter requires a characteristic similar to those for power transformers. It was not clear to the WTEC panel who had developed the wire for the limiter, but it is likely that the TEPCO project supported the wire development component.

APPLICATIONS OF LOW T_C SUPERCONDUCTORS FOR VERY HIGH MAGNETIC FIELDS

Nb_3Sn Conductors

The Japanese government through the Science and Technology Agency (STA) has been a very strong supporter of the development of a power reactor based on magnetic confinement of plasma, and STA has been a major sponsor of the ITER project. In this project, Nb_3Sn conductors that are used to produce very high fields ($H \approx 13$ T) in a large volume play a key role. The two processes used to produce the conductors are the bronze and the internal tin processes: the first is the oldest and most commonly used process to manufacture wire for high field applications; the latter is also quite extensively used, particularly in the United States.

Even though the internal tin process was developed at Mitsubishi Electric Company in Japan in the early 1970s, it was not used at all in Japan until very recently. It was interesting to the WTEC panel to find that Mitsubishi had reentered the field of manufacturing Nb_3Sn wires by the internal tin process after many years of being absent. In this process, coalescence of the Nb_3Sn filaments has been one of the major difficulties. The coalescence of the filaments causes enlargement of the effective size of the filaments and thus leads to increased hysteresis loss. Mitsubishi researchers performed an extensive metallurgical study of the mechanism for the coalescence and were able to find fabrication steps that minimized this problem. The result of this development is that Mitsubishi has now become one of the suppliers of Nb_3Sn wires to the ITER project, and, of importance to other manufacturers, the process appears to be less costly than the bronze process.

Nb_3Al Conductors

The other interesting development in Japan for high field conductors is the successful fabrication of large-sized Nb_3Al conductors suitable for use in the ITER project. This superconductor has been studied extensively in the past since it can be made to have a higher T_c (20 K) than that for Nb_3Sn. More importantly, its critical current is less sensitive to mechanical strains; however, Nb_3Al conductor has turned out to be very difficult to produce in large quantities. Because of the enormous forces involved in the ITER type of magnet, ITER engineers have been very interested in the mechanical properties of Nb_3Al wire, and those involved in the ITER project at the Japan Atomic Energy Research Institute (JAERI) have been encouraging Japanese manufacturers to develop Nb_3Al as a conductor for the ITER project. Sumitomo Electric Industries was the first to successfully produce ITER-sized conductor capable of meeting the critical current requirement. Following this, Hitachi in collaboration with Hitachi Cable also reported manufacture of the conductor. Some other companies in Japan are also known to be working on Nb_3Al. The fact that Japan is the only country working on this development is noteworthy; that no U.S. effort exists perhaps reflects the financial difficulties that the U.S. magnetic fusion community is experiencing.

The Nb_3Al conductors are fabricated using the so-called “jelly-roll” method, which has been known for a number of years. In principle, the process is very simple. Thin foils of Al and Nb are wrapped around a core, and a large number of these elements are then packed into a Cu tube and drawn to size and heat treated for forming Nb_3Al by interfacial reaction. In practice, it is difficult to uniformly reduce the thickness of the foils to tens of nanometers before the reaction. In spite of this, there are now two or three manufacturers in Japan that can produce this conductor on a large scale.

SUMMARY

There are extensive efforts in Japan aimed at the development of low T_c superconductors tailored to each of several large projects, such as Super-GM and ITER. These are primarily sponsored by the Japanese government, although the associated industrial contribution (e.g., cost sharing) toward the development of conductors is thought to be even greater than the government’s contribution. One key to Japan’s continued development of low T_c conductors is the fact that the Japanese government has continued to fund large construction projects involving the applications of superconductors. Each of these projects requires development of improved conductors, and in turn, the manufacturers of the wires can maintain the experienced staff to sustain the R&D on superconducting wires. It will be very interesting to observe whether Japan will continue to work on low T_c superconductors when some of the high T_c superconductors are getting to the stage at which utility applications of these conductors may become realistic in the relatively near future.

APPENDICES

APPENDIX A. PROFESSIONAL EXPERIENCE OF PANEL MEMBERS

David C. Larbalestier (Panel Chair)

Dr. Larbalestier is a professor in the Department of Materials Science and Engineering and in the Department of Physics at the University of Wisconsin in Madison, where he holds the L.V. Shubnikov Professorship and the Grainger Professorship of Superconductivity. Since 1992 he has been the director of the Applied Superconductivity Center, an interdisciplinary center of 10 groups and about 80 participants. He has been awarded the Matthey Prize (University of London), an IR-100 award (1978), the 1991 IEEE Particle Accelerator Conference award (jointly with Ronald Scanlan of Lawrence Berkeley Laboratory), and he is a Fellow of the American Physical Society. He has served on review panels of the National Science Foundation and the Department of Energy and was also a member of the National Academy of Sciences Panel on High Temperature Superconductivity. He has published more than 200 scientific papers and has been invited to give more than 80 presentations at scientific meetings.

Richard D. Blaugher

Dr. Blaugher is a principal scientist at the National Renewable Energy Laboratory (NREL) and Program Manager for the NREL high temperature superconductivity research. He provides the primary technical support to the Department of Energy (DOE) Superconductivity Partnership Initiative administered by the DOE Golden Field Office. He has an extensive background in superconductivity that spans over 30 years. Prior to joining NREL, he was manager of the Superconductivity and Electronics Department at the Westinghouse R&D Center until 1988, then managed high temperature superconductor research at Intermagnetics General Corporation (1988-91). He has served on various government committees on superconductivity and has also served on the boards of *Applied Superconductivity* and *Cryogenic Engineering*. He has published over 90 papers and review articles related to cryogenic and superconducting materials.

Robert E. Schwall

Dr. Schwall is Vice President of Engineered Products at American Superconductor Corporation (ASC), where he is responsible for all magnet and systems activity; this includes electromagnets, motors, generators, and cryogenic subsystems. Prior to joining ASC Dr. Schwall spent 9 years with IBM, where his work concerned superconducting magnets for magnetic resonance imaging (MRI), operation of semiconductors at low temperatures, and development of optical tooling. Earlier he spent 9 years at Oak Ridge National Laboratory and at Intermagnetics General Corporation in the areas of superconductive materials and devices. He received his BS in Physics from St. Mary’s University of Texas and his MS and PhD in Applied Physics from Stanford University. He is the author of more than 50 papers and patents in the fields of superconductivity and cryogenics.

Robert S. Sokolowski

Dr. Sokolowski is responsible for all operations of Intermagnetics’ superconducting materials business. Previously, he directed the company’s high temperature superconductor (HTS) program and was, for eight years, with Allied Signal (amorphous metals) and Olin Corporation (thin-strip casting of nonferrous alloys).

Prior to joining Intermagnetics, he was responsible at NASA headquarters for a $60 million program in microgravity materials science. He was also responsible for international coordination of cooperative R&D at NASA’s Marshall Space Flight Center, as program scientist for international Spacelab missions. He was Chief of Solidification Physics, the Center’s Assistant Space Station Scientist, and U.S. Microgravity Laboratory-1 Mission Scientist, and also served as a member of the Federal Coordinating Committee on Science, Engineering, and Technology. He received his BS and PhD (Materials Engineering) from Rensselaer Polytechnic Institute, Troy, NY. He holds process patents in continuous casting and has published articles in the areas of solidification, microgravity applications, and high temperature superconductivity.

Masaki Suenaga

Dr. Suenaga is a senior metallurgist and group leader of the Superconducting Materials Group in the Materials Science Division of Brookhaven National Lab (BNL). He specializes in superconducting materials, mechanical properties, phase stability, and applications of electron microscopy. In the past he was head of the Metallurgy and Materials Science Division of BNL (1978-86), was a member of the Review Committee for the Materials and Chemical Science Division at Lawrence Berkeley National Laboratory, and board member of International Cryogenic Materials Conference and Applied Superconductivity Conference. He is currently adjunct professor of Materials Science at the State University of New York at Stony Brook, NY.

Jeffrey O. Willis

Dr. Willis has been a technical staff member in the Superconductivity Technology Center (STC) at Los Alamos National Laboratory since the STC was founded in 1988 to conduct research and development in high temperature superconductivity (HTS). He conducts research on the physics and materials science of HTS materials, primarily of bulk HTS wires and tapes, and is the technical coordinator at the STC for bulk conductor R&D. He has authored or co-authored more than 120 technical journal articles on HTS and on other superconducting and magnetic materials during his professional career. He received a BS in Engineering Physics and MS and PhD (1976) in Physics from the University of Illinois at Urbana-Champaign. He has been employed at Los Alamos National Laboratory since 1978. He was a visiting scientist for 1½ years (1990-91) at the Superconductivity Research Laboratory of the International Superconductivity Technology Center (ISTEC) in Tokyo, Japan, and spent six months at Tohoku University’s Institute for Materials Research in 1997. Willis has been a participant in the US/Japan Workshop on Superconductivity since 1992, and he completed the two-year Japanese Industry and Management of Technology program at the University of New Mexico in 1994. He is a member of the American Physical Society and the Materials Research Society.

APPENDIX B. PROFESSIONAL EXPERIENCE OF OTHER TEAM MEMBERS

James G. Daley

Dr. Daley is manager of the Department of Energy (DOE) Superconductivity Program in the Office of Utility Technologies. This is the lead federal effort for energy applications of high temperature superconductivity. The DOE Superconductivity Program supports a broad technology base effort at government, university, and private laboratories, and a sizable portfolio of development projects, including two transmission cable projects, an industrial motor project, a fault-current limiter project, a generator project, and a transformer project. Dr. Daley was a staff scientist at Argonne National Laboratory for 15 years before joining the Department of Energy, performing research in a variety of fields that included nuclear energy, advanced heat engines, and electric utility storage systems. His industrial experience includes work at General Electric's Transportation Systems Division and United Technology's Pratt and Whitney Aircraft Division. He has published widely in journals and reports. He holds a PhD in Mechanical Engineering (Thermodynamics) from the University of Connecticut.

George Gamota

Dr. Gamota is president of Science and Technology Management Associates, a technology consulting firm specializing in technology assessments, research and technology policy, and small business development. He is senior advisor to the World Technology Evaluation Center (WTEC) program, which assesses trends in international science and technology for the National Science Foundation (NSF) and other U.S. government agencies. He played a key role in the founding of the WTEC program. Dr. Gamota also serves as Director of WTEC's sister organization at Loyola College, the Technology Transfer and Education Center (TTEC), which is primarily engaged in organizing business incubators in Ukraine under a cooperative agreement from the U.S. Agency for International Development. He previously served as chief scientist of the MITRE Corporation's Bedford Group, president of Thermo Electron Technologies Corporation, professor of Physics and director of the Institute of Science and Technology at the University of Michigan, director for research in the Office of the Secretary of Defense, and special assistant to the President of Bell Laboratories. At Bell Laboratories he did basic research in low temperature physics, including low temperature superconductivity. He was the 1995 national chairman for the National Conference on the Advancement of Research. He holds a PhD in Physics from the University of Michigan (1966). Dr. Gamota has received the Secretary of Defense Meritorious Service Award and certificates of appreciation from the Presidential Management Interns and the Minority Technology Council of Michigan. He is a fellow of the American Association for the Advancement of Science (AAAS) and the American Physical Society (APS), and he is a senior member of the IEEE.

Paul M. Grant

Dr. Grant is an executive scientist at the Electric Power Research Institute (EPRI), with responsibility for EPRI's program in superconductivity and advanced power electronics. From 1986 to 1990 he coordinated and managed the high temperature superconductivity effort at the IBM Almaden Research Center. Among his accomplishments during this period were sharing in the discovery of the structure of $YBa_2Cu_30_{7-y}$, the first material to superconduct above the boiling point of liquid nitrogen, and its optimum processing conditions, as well as the discovery of high temperature superconductivity in undoped La_2Cu0_{4+y}, the parent compound to the original Bednorz-Mueller discovery. From 1990 to shortly before his retirement from IBM in 1993, he was on sabbatical as visiting full professor at the Materials Institute of the National University of Mexico. Dr. Grant is author or coauthor of more than 100 technical papers, in addition to more than a dozen articles in the popular literature and press.

Donald U. Gubser

Dr. Gubser is superintendent of the Materials Science and Technology Division at the Naval Research Laboratories (NRL). He received his PhD (1969, Physics) from the University of Illinois, and since that time he has been employed at NRL, where he has specialized in superconductivity, magnetism, and cryogenic properties of materials. In 1976, he spent one year of advanced graduate training at the Swiss Federal Technical University (ETH) in Zurich, Switzerland, conducting research on superconductors. He headed the Condensed Matter Sciences section of the Division of Materials Research at NSF in 1985. He is also a professorial lecturer in materials science at George Washington University. In 1983 Dr. Gubser received the Naval Meritorious Service Award for his scientific leadership and research accomplishments, and in 1992 he received the Senior Executive Service Meritorious Service Award for excellence in science management. He is Chairman of the Naval Consortium for Superconductivity, and is coeditor of the *Journal for Superconductivity*. Dr. Gubser is a fellow in the American Physical Society (APS) and secretary-treasurer of the Division of Condensed Matter Physics of the APS.

APPENDIX C. JAPANESE SITE REPORTS

Site:	**Central Research Institute of the Electric Power Industry (CRIEPI)** **Superconductivity Department** **2-11-1 Iwatokita, Komae-shi** **Tokyo 210, Japan** **http://criepi.denken.or.jp**
Date Visited:	7 June 1996
WTEC Attendees:	P. Grant and J. Daley (report authors), R.D. Blaugher, G. Gamota, R. Schwall, R. Sokolowski
Hosts:	Kiyotaka Uyeda, Associate Vice President Shirabe Akita, Director, Superconductivity Department

BACKGROUND

The Central Research Institute of Electric Power Industry (CRIEPI) was founded in 1951 when the Japanese government dismantled the Japan Power Generation and Transmission Company and the nine power companies according to an order to reorganize the electric power industry based on the Potsdam Ordinance. CRIEPI was formed as the electric-utility-related R&D laboratory to support the nine new private regional utilities that are in existence today. CRIEPI is managed through a fund using a 0.2% “tax” placed on all electric energy sales in Japan by the privatized utilities. In comparison, the U.S. Electric Power Research Institute (EPRI) in the past collected its funds via a similar surcharge on the generation capacity of its member utilities that state regulatory commissions allowed to be passed on to the ratepayers. The difference is that membership in EPRI is voluntary, and with deregulation, the incentive to join EPRI has diminished. As far as the WTEC panel could see, CRIEPI faces no immediate similar situation, and indeed its funding is likely to grow as load growth continues to increase in Japan, unless political events intervene. Over the years, several of the largest of these nine utilities, notably Tokyo Electric Power Co. (TEPCO), Kansai Electric Power Co. (KEPCO), and Chubu Electric Power Co., have created their own R&D centers. The division of effort between CRIEPI and the utility laboratories seems to be that “basic” R&D and system modeling and analog simulation is done at CRIEPI, and prototype development (e.g., cable, generators, flywheels, etc.) is done at utility labs in conjunction with both industry and government.

Principal superconductivity programs at CRIEPI center around materials and ac loss measurements. In the past, CRIEPI researchers have done extensive ac loss testing on LTS wires. Similar measurements have been done on HTS materials, including some interesting studies indicating lower loss ac transport at elevated frequencies in the reversible region of the mixed state. HTS material work centers on collaboration with Tokai on diffusion thalination and a new facility to investigate grain angle boundary effects in YBCO (it is not clear in this area what problems CRIEPI will address that are not already addressed elsewhere, e.g., at the University of Wisconsin). In addition, CRIEPI advises and proposes to the Japanese government programs on superconductivity (e.g., Super-GM) in the interest of the electric utilities. The superconductivity group is very small compared to other departments in CRIEPI, but is “special” in the sense that it and one other department (biotech) are dedicated to long-term technologies.

Personnel

Akita’s Group: 8

Budget (exclusive of salaries)

Internal:	$1.6 million/year
External:	$0.15 million/year (Super-GM study)
	$0.06 million/year (SMES study)

ANSWERS TO QUESTIONS

Question: What do you see today as CRIEPI’s most important effort in R&D for HTS power applications?
Answer: 1st, Cable; 2nd, FCL.

Question: What HTS products does your organization have for sale now or has it already announced for sale in the near future? Could you supply product literature or specifications for these products?
Answer: A8: Power Cable.

Question: What is your organization’s most significant contribution to achieving practical HTS conductors?
Answer: Understanding of grain boundary problem.

Question: What are the major scientific and technical issues for these materials?
Answer: Grain boundaries and flux dynamics.

Question: What are the most favorable HTS material and conductor geometry for the applications your organization is targeting?
Answer: Cable, FCL.

Question: What are the most important problems limiting critical current density (J_c) in wires and tapes produced by the powder in tube (PIT) or coated conductor process?
Answer: Grain boundaries.

Question: What are the target costs and markets for this technology?
Answer: 1 ¥/Am., dc, Nb-Ti at 5 T ($10/kAm).

Question: What are the major scientific and technical issues for these applications (generation and storage).
Answer: Simulations/analysis.

Question: For power transmission cables, what is your organization’s approach to cable design, particularly with respect to electrical and thermal insulation materials, conductor geometries and physical placement, and termination (connection to room temperature conductors) design?
Answer: Cryocooled cable.

An interesting discussion occurred during the WTEC visit regarding high T_c generators and motors. CRIEPI management would like to start a collaboration in the near future. It would involve only high T_c generators and motors. Uyeda planned to visit the United States, and hoped to learn more about the Reliance-SPI. The panel’s hosts viewed any Japanese program as a nongovernment effort. High T_c generators and motors are another example of the new large SC projects waiting to be started.

CRIEPI management is interested in participating in an international effort to define ac loss standards and has offered to provide the “interface” to Japanese wire and cable companies in providing samples and acting as one of the test sites.

Site: **Chubu Electric Power Company, Inc.**
Electric Power Research & Development Center
20-1 Kitasekiyama, Ohdaka-cho, Midori Ku
Nagoya, Aichi-ken, Japan
http://www.chuden.co.jp

Date Visited: 7 June 1996

WTEC Attendees: R.D. Blaugher (report author), J. Daley, G. Gamota, P.M. Grant, H. Morishita, R. Schwall, R. Sokolowski

Hosts: Isamu Kobayashi, General Manager
Kimio Kamiyama, Deputy General Manager
Shigeo Nagaya, Director, Superconductivity R&D
Hideki Fujita
Suresh Chand Verma

BACKGROUND

Chubu Electric Power Company, Inc., founded in 1951, is the third-largest electric utility in Japan behind Tokyo Electric Power Co. (TEPCO) and Kansai Electric Power Co. (KEPCO). Chubu delivered 113 billion kWh to its customers in 1995 with an operating revenue of $21 billion. Chubu employs approximately 21,000 people and has 208 in its Research & Development Bureau with a budget of ~$70 million. Chubu's total R&D budget is approximately $150 million. The superconductivity group of seven people (plus seven others) is located within the Electric Power Research & Development Center, which has 117 staff members. The estimated budget for superconductivity, including salaries, is ~$750,000, which is split between SMES and HTS. All of this R&D support is completely internally funded. Additional income is obtained from patents held jointly by Chubu, which retains 50% of the royalties.

SUPERCONDUCTIVITY RESEARCH AND DEVELOPMENT

Largely as a result of having ~20% hydro capacity, Chubu management became interested in the development of SMES as early as 1988. The efficiency for pumped-hydro is low (65-75%); hence, more efficient energy storage technologies such as SMES and flywheels are attractive for providing additional capacity and load leveling capability. Chubu and Hitachi manufactured and tested in 1989 a 1 MJ SMES using Cu/Cu-Ni-stabilized Nb-Ti (7 µm filaments) conductor. The test results showed the expected fast response necessary for system stabilization but with much higher than expected losses in the power conditioning. Chubu management nevertheless was encouraged, and the SMES effort continued internally up to 1991, at which point the internal work was terminated in favor of an external participation in the national ISTEC/SMES program.

The internal SMES effort was redirected in 1994 towards flywheels in collaboration with Mitsubishi and Dowa Mining. The long-range objective for flywheels is development of 1 MWh flywheels to be installed in a large flywheel park comprised of 10 flywheels. Chubu researchers are currently developing a 60 cm flywheel using permanent magnets and 6 cm YBCO bearings with 9 SC/PM assemblies mounted on a ring. The flywheel is to weigh ~180 kg and operate at 10,000 rpm (~0.3 kWh). Higher-speed operation at 20,000 rpm would produce ~1.4 kWh. Chubu researchers are also looking at SC transmission in collaboration with Fujikura on the Bi-tape conductor and with Sumitomo on terminations. Chubu is fabricating short cable lengths for demonstration, with longer lengths under development. The terminations have already been developed and tested with excellent performance. The researchers reported on this activity at the August 1996 IEEE summer meeting. They estimate that 5 x 10^5 A/cm^2 is needed for SC transmission.

SUPERCONDUCTOR MATERIALS RESEARCH

Chubu is internally fabricating fairly large (10 cm) YBCO melt-processed “hockey pucks” for the flywheel bearings. Dowa Mining is also involved in the bulk material development. All the Bi-tape conductor work for the transmission effort is carried out in collaboration with Fujikura. Chubu researchers, however, are internally looking at the deposition of YBCO using CVD. The need for low ac losses for superconducting cables is identified as a major concern.

GENERAL OBSERVATIONS

- Chubu management expects R&D on SC-related power applications to continue with high interest for at least another ten years.
- The funding and personnel involved in superconductivity within Chubu should be flat, with no growth or reduction anticipated.
- Storage is the most important activity for Chubu, with flywheels the preferred technology. SMES is thought to be too expensive. Storage is important compared to alternatives, such as gas-fired units, due to environmental issues.
- Chubu management feels SC transmission has enormous potential for long-length transmission with cooling stations located at 10 km intervals.
- Chubu does not anticipate or expect the use of SC devices in the electric power system for at least 20 years.

Site:	**Fujikura, Ltd.** **Superconductivity Research Department** **Materials Research Laboratory** **1-5-1, Kiba, Koto-ku** **Tokyo 135, Japan** **http://www.fujikura.co.jp/fujikuev.htm**
Date Visited:	7 June 1996
WTEC Attendees:	J. Willis (report author), D. Gubser, D. Larbalestier, M. Suenaga
Hosts:	Nobuyuki Sadakata, Manager, Superconductivity Research Dept., Materials Research Laboratory

BACKGROUND

Fujikura, Ltd., was established in 1885 in Tokyo to manufacture rubber insulated electrical wire and was incorporated as Fujikura Cable Works, Ltd., in 1910. The headquarters and plant were moved to their present site in Koto-ku, Tokyo, in 1923. This is also the location of the Tokyo R&D Center. Fujikura has three manufacturing plants in the Tokyo area and one near Nagoya. Fujikura has sales and manufacturing facilities in the Americas, including the United States, in Europe, and in Southeast Asia. These are about 50% owned by Fujikura and together contribute about 20% to total sales. Fujikura Cable Works, Ltd., was renamed Fujikura, Ltd., in 1992 to reflect the corporate goal to pursue non-cable business areas.

BUSINESS

Fujikura's original and still largest business area (approximately 70% of sales in 1995) is electric wire and cable, which includes products such as telecommunication cable, magnet wire, rubber- and plastic-insulated wire, and power transmission systems, including a new 500 kV underground cable. The second area is fiber optics and related products (19% of total sales). The third and a rapidly growing area is electronic materials and components (11% of sales), including such items as sensors, interface cables, flexible printed circuit boards, and membrane switches. Fujikura has been hard hit by the recession in Japan since 1991 and further by the appreciation of the yen in 1995. It restructured in October 1994 to respond to the recession. Net sales and net income have both been decreasing since 1991. Because of weak domestic demand, decreases in the wire and cable area have only been partially offset by increases in the other two product areas. For the year ending 31 March 1995, net sales and net income were $2.428 billion and $15 million, respectively. R&D expenditures were $106 million for the same period. The company's workforce grew to an all time peak of 4,365 in 1992, decreased by 100 in 1993, and then by another 100 in 1995 to 4,101.

SUPERCONDUCTOR RESEARCH AND DEVELOPMENT

Fujikura's R&D functions take place in five laboratories: Materials Lab, Advanced Technology Lab, Optoelectronics Lab, Energy Systems Lab, and Fujikura Technology America Corp. (FTAC). The Materials Research Lab has three divisions: Metallic Materials, Polymers and Chemicals, and Superconducting Materials. High temperature superconductor (HTS) R&D takes place at the Tokyo R&D Center. Metallic (low temperature superconductor, LTS) R&D and HTS wire manufacturing is done at the Numazu plant in Shizuoka Prefecture, about a one-hour train ride outside Tokyo. There are 20 researchers and technicians working on superconductivity. Of these, approximately 1/3 are working on LTS and 2/3 on HTS materials. Partial support of R&D activities comes from the New Energy and Industrial Technology Development Organization (NEDO) Super-GM project and through power companies, primarily Chubu Electric Power Company. These funding sources generally contribute less than half of the research funds for a particular project. Recent R&D at Fujikura focuses on research entrusted and consigned by NEDO (similar to contract work in the United States) and on collaborative research, always with shared funding, with electric power companies, universities, or national laboratories.

Fujikura management sees its most important R&D efforts to be on power transmission lines, generators, magnets, and current leads. Fujikura had no LTS or HTS products for sale at the time of the WTEC team's visit. Estimates of the future market for HTS products are \$10 million, \$100 million, and \$5 billion in five, ten, and twenty years, respectively.

LTS

Fujikura has been active in superconductivity since 1970 when it began work on the development of force-cooled hollow conductors for fusion magnets using both Nb-Ti and Nb_3Sn in collaboration with MITI's Electrotechnical Laboratory (ETL). Fujikura then developed an internal tin plating method for Nb_3Sn wire production based on commercial 6% Sn bronze matrix material. It also developed a large current (10 kA at 10 T) Nb_3Sn hollow conductor in 1983. Starting in 1988, Fujikura began doing R&D for the Super-GM national project. Fujikura developed an *in situ* processed Nb_3Sn wire for the field coils of the 70 MW-class superconducting generator. The 1 kA ac wires have high mechanical strength and fine filaments (0.5 µm) for low ac losses. In a collaboration with Tohoku University begun in 1990, Fujikura has been developing a reinforced Nb_3Sn wire using a CuNb stabilizer for the conductor in the outer magnet (60-100 cm ID) of a hybrid magnet located at the university; the inner coil is a water-cooled copper magnet. The wire performed up to the very high stress levels of 224 MPa at 9 T during testing. Since 1991, Fujikura has been working in collaboration with Tohoku Electric Power Co. to produce a magnetically controlled 1 kA-class, fast response (20 ms) persistent current switch (PCS) for a small, quick response SMES for electric power conditioning. Finally, in 1993, Fujikura began development of a 600 A Nb-Ti ac conductor for a coreless autotransformer in a collaboration with ETL. This requires cabling of wires to achieve the current required and fine filaments to achieve a low ac loss conductor. Fujikura sells few LTS products; it mainly produces R&D materials.

HTS R&D

Fujikura started oxide superconductor work in 1986, focused in three main areas: Y-123 coated conductors, Bi-2223/Ag sheath tapes, and Y-123 bulk rods. There are 12-13 researchers working in this area, divided about 40%, 40%, and 20%, respectively, between these three categories.

Fujikura pioneered and had the earliest successes with the ion beam assisted deposition (IBAD) process for preparing a biaxially textured buffer layer of yttrium-stabilized zirconia (YSZ) on top of a polycrystalline nickel alloy (Hastelloy) substrate. One ion gun is directed at the YSZ source and causes deposition of YSZ on the Hastelloy substrate while a second assisting ion gun directs Ar ions at the substrate at an angle near 55°, which has the effect of causing the YSZ film to be biaxially oriented (<100>) with respect to the substrate. Figure 5.12 (p. 73) shows the IBAD apparatus. A YBCO superconductive film is then deposited on the YSZ buffer layer by conventional deposition techniques, such as pulsed laser deposition (PLD). This film grows epitaxially on the YSZ and shows good c-axis and a-b-plane orientation, and as a result, good critical current density (J_c) properties. Figure 5.3 (p. 65) shows the layers in the conductor. Transmission electron microscope (TEM) orientation analysis of Fujikura's YBCO films shows that more than 50% of the grain boundaries have misorientation angles of less than 5°, and ~80% have angles of less than 10°. In addition, fewer dislocations are observed near the low angle grain boundaries. Short sample (1 cm) J_c values for a 0.4 µm thick film are greater than 1 MA/cm^2. At the time of the WTEC visit, the most recent long length result for this process was 0.17 (+/- 10%) MA/cm^2 and 18.1 A at 77 K and 0 T for an 0.8 m long, 1 cm wide, 1 µm thick Y-123 film. Y-123 films can be deposited at a rate of 1 m/h. This work is being done as an entrusted research of Super-GM, supported under the New Sunshine Program of AIST, under MITI, and consigned by NEDO.

For the IBAD process films to be used as long length conductors, it is necessary for the production process to be rapid. To accomplish this, Fujikura is also using metallorganic chemical vapor deposition (MOCVD) to deposit the YBCO on Hastelloy substrates 0.2 mm thick by 5 to 10 mm wide with an intermediate length goal of 1 m. The goal is to develop a continuous process for depositing a 10 µm thick YBCO film 10 m or more in length. Present issues being investigated are the presence of a barium zirconate reaction layer 15-20 nm thick on the YSZ buffer layer. The depletion of Ba may be responsible for the formation of second-phase precipitates of CuO in the rest of the film; these precipitates are thought to be responsible for the variation in J_c along the tape length. Also being investigated is the control of oxygen partial pressure by feedback from a residual gas analyzer. The oxygen partial pressure tends to change during a deposition in the hot wall reactor, resulting in Y-123 film stoichiometry variation. The best MOCVD deposited Y-123 on an IBAD YSZ buffer layer on Hastelloy yielded 0.21 MA/cm^2 and 17 A at 77 K and 0 T over 16 cm; the highest J_c value over 1 cm is 0.6 MA/cm^2. Film deposition rate is about 0.5 m/h. As yet, the thickness uniformity, alignment, and phase purity of the Y-123 films are not as high as that produced by PLD. This work is being done in collaboration with Chubu Electric Power Company.

Bi-2223/Ag sheathed 37-filament tape is being produced for use in an electric utility power cable. Fujikura has investigated fundamental issues, such as the effect of particle size on Bi-2223 phase formation, and practical properties, such as ac losses for tapes singly and in conductor configurations. Fujikura has recently designed a model flexible cable 150 mm in diameter to operate at 77 kV with cooling stations every 5 km. A 5 m long prototype was constructed using 37-filament Bi-2223/Ag tapes arranged in 10 stacks spaced radially in a 20 mm ID, 45 mm OD conductor. This carried 1.2 kA both before and after insulating with a semisynthetic paper and after fully fabricating the thermal insulation and outer sheaths. This work is also being performed in collaboration with Chubu Electric Power Company.

Bulk Y-123 current leads have been produced for power applications. The Y-123 is doped with Y-211 and Pt and Ag additions, cold isostatically pressed into rods 2-3 mm in diameter and 2-10 cm long, presintered, then directionally melted and solidified with a toroidal heater. It was found here (other groups have reported similar results) that Y-211 forms small pinning centers and that adding Pt constrains the size of the Y-211 precipitates and adding Ag helps prevent cracking. Fujikura has explored doping levels and obtained I_c values of 1,500-1,800 A and J_c values of 33 kA/cm^2 at 77 K, 0 T for the best rods 2-3 mm in diameter over a 2 cm gauge length. The Ag and Pt additions greatly improved the surface roughness of the melt-processed rods. Optimum conditions were achieved for Y-211 additions of 10:3 or 10:5 (Y-123:Y-211), Ag content of 5 wt %, and Pt content of 0.5 or 1 wt %. Growth rates of 1 mm/h gave slightly better results than at 3 mm/h. This work is being done in collaboration with Chubu Electric Power Company.

SUMMARY

Fujikura is producing high quality conductors and making important contributions to LTS applications, which continue to be supported by the national government and power companies. In the HTS area, Fujikura is one of the leaders in Y-123 coated conductor work and is also producing prototype power transmission cables. Continuation of HTS R&D at Fujikura will require ongoing external support.

Site: **Furukawa Electric Co., Ltd.**
Nikko Works
500, Kiyotaki, Nikko-shi,
Tochigi-ken 321-14, Japan
http://www.furukawa.co.jp/english/cover.htm

Date Visited: 3 June 1996

WTEC Attendees: J. Willis (report author), R.D. Blaugher, D. Gubser, D. Larbalestier

Hosts: Masaru Ikeda, General Manager, Superconductivity Research Dept., R&D Division
Shin-Ichiro Meguro, General Manager of Sales Engineering, Superconducting Products Dept., New Business Development Div.
Naoki Uno, Manager, Superconductor Section, Superconductivity Research Dept., R&D Division
Dr. Yasuzo Tanaka, Chief Engineer, R&D Division

BACKGROUND

Furukawa Electric Company, Ltd., was founded in 1884 and is a leading producer of electric wire in both Cu and Al forms. The Nikko Works, located in a resort town of great beauty, is nestled (some would say confined) in a valley and combines both traditional Cu smelting and large product manufacture with low volume, high value added products. The work at Nikko is organized into several product divisions: Casting, Wire and Rod, Strip, Special Metals, and Bare Conductor, and the R&D Division. There are about 1,500 employees at Nikko, about 1,000 in Cu products (output of 9,000 tons/month) and about 500 in Al products (output of 4,000 tons/month). The company as a whole employs a total of about 9,000 persons. Furukawa's major customers are Tokyo Electric Power Company (TEPCO) and aluminum can producers. The WTEC team's visit was with staff coming primarily from the R&D Division and with one member of the New Business Development Division, where the superconducting wire manufacture is carried out. Most of Furukawa's superconductivity-related work is performed at the Nikko Works.

SUPERCONDUCTIVITY BUSINESS

Furukawa has long been in the superconductor business, starting in 1963 just after the discovery of high field superconductivity. It is and has been a supplier of a broad range of high quality LTS wire, both Nb-Ti and Nb_3Sn. It was also a manufacturer of MRI magnets in a joint venture with Oxford Instruments, but this has now lapsed, and its MRI business is limited to maintenance of existing MRI systems in Japan through an affiliate called Superconducting Magnet Service Company. From all suppliers there are about 3,000 MRI systems in Japan. Furukawa Electric is a special supporting member of the International Superconductivity Technology Center (ISTEC) and has employees at ISTEC's Superconductivity Research laboratory (SRL). Furukawa also supplies personnel to the Super-GM (Superconducting Generator and Materials) project of the Ministry of International Trade and Industry (MITI), contracted through the New Energy and Industrial Technology Development Organization (NEDO). A booklet of Furukawa's 1995 publications related to superconductivity contains reprints of nearly 30 articles and is 133 pages long.

Furukawa's present work in superconductivity covers several product lines within the New Business Development Division's Superconductivity Products Department. Foremost among these is wire and cable for magnet systems. When the WTEC team visited, a recent large order was for 7.6 tons of bronze-route Nb_3Sn for the International Thermonuclear Experimental Reactor (ITER). This is the largest share of the Japanese Nb_3Sn ITER order, other parts of which went to Hitachi Cable (2.0 tons) and Mitsubishi Electric (4.0 tons). Furukawa has also produced aluminum-stabilized Nb-Ti conductors for a 30 kA bus line of the Large Helical Device. The company has also completed a Bi-2223 cable for TEPCO. The cable is 38 mm in diameter, 50 m long, and has a 77 K I_c of 1,700 A and a steady state ac current capacity of 1,200 A rms. The company has supplied a coaxial Pb cable for an anti-proton ring at Fermilab in the United States, and some laboratory magnets fabricated from Nb-Ti and Nb_3Sn that produce fields up to 15 T.

Personnel, Budget, and General Topics

Furukawa has a total of ~50 people working on superconductivity, of whom 30 are in the products department and 20 are in R&D, which is divided into LTS and HTS. The total budget for all superconductivity-related activities varies between $5 and $10 million with time, depending on the specific R&D projects being worked on. There has been a small decrease in the HTS budget from previous years. Most Furukawa projects are jointly funded, typically 66-75% from internal funds, the remainder from national projects or power companies. For jointly funded projects, external money is used to cover R&D and salary expenses. Furukawa occasionally supports small (<$100 thousand) collaborative projects with universities. Furukawa's most important project for HTS power applications is the power transmission cable. A few products, such as current leads and magnetic shields for magnetoencephalography (MEG), are available now, but management does not see a large market because these items are still really in the R&D stage. Small products may come to market in 5 years, and larger items, such as the power transmission cable, will be available in 10-20 years. Furukawa representatives did not make predictions of market size, except to say that it is rather small now.

HTS Conductor Development

About 50% of Furukawa's HTS R&D budget and manpower are devoted to conductor development, with all work being on Bi-2212 and Bi-2223. Some of this work is in collaboration with the Super-GM national project. External organizations contribute about 50% of the funds for conductor development. The standard production material is 400 m long Bi-2223/Ag powder-in-tube tape with performance values at 77 K and self field of critical current $I_c = 30$ A, critical current density $J_c = 20$ kA/cm^2, and engineering (overall) critical current density $J_e = 8$ kA/cm^2. The comparable values for Bi-2212/Ag tape at 4.2 K, self field are $I_c = 150$ A, $J_c = 370$ kA/cm^2, and $J_e = 70$ kA/cm^2. Furukawa researchers see a limiting factor for further development as low J_c, which ultimately is determined by careful process control to produce good texture and eliminate second phases. Silver alloys are used to reduce ac losses or to improve strain sensitivity in some applications. Target costs are $10/kAm for 77 K cable applications and 3-10 times this value for coil applications.

Generation and Storage

Furukawa has been a member of the Super-GM project since its inception in 1988. Its major contribution is the design and manufacture of quick-response type (LTS) cable for the 70 MW superconducting generator. It also participates in the ISTEC-led national project to develop a 0.1 MWh, 480 MJ SMES. Furukawa is making the cable-in-conduit (CIC)-type LTS cable for a model coil. As part of a different SMES project, Furukawa is making a mixed matrix-type Rutherford cable for KEPCO's 1 kWh, 1 MW (3.6 MJ) coil. Bronze process Nb_3Sn wire for the ITER project completes this category and represents 50% of Furukawa's LTS projects. These are all products of the New Business Development Division, and although there is no discrete R&D component for a project, some production engineering is always required.

Transmission and Distribution

About 25% of Furukawa's R&D funds are devoted to this application area. The main effort is for the power transmission cable, with smaller efforts on fault-current limiters and transformers, all of which have about 50% external funding from power companies. The power cable project, still in the R&D stage, is targeting a 1 GW, 66 kV cable, double the power of standard underground cable.

Furukawa has already developed a 5-meter-long prototype superconducting cable and a 50-meter-long conductor for the power transmission cable using Ag-sheathed Bi-2223 phase multifilamentary tapes in collaboration with Tokyo Electric Power Company (TEPCO). Furukawa has successfully performed a 66 kV, 2 kA peak load test for the 5-meter-long cable, and 2 kA$_{rms}$ current test and ac loss measurements for the 50-meter-long conductor. AC losses were measured on the whole length of the conductor by changing transport currents of each isolated layer using insulation with externally connected variable resistors. The results were analyzed using the standard Norris's equation and the Uniform Current Distribution Model (UCD Model) introduced by Furukawa, which makes different assumptions about the current distribution.

Furukawa's major role in these projects is as a supplier of wire and cable, although it also performs a full range of functions from design to cost evaluation. Major technical issues are enhancement of the engineering properties of the conductor, electrical insulation, and refrigeration.

End User Applications

This constitutes the remaining 20-30% of Furukawa's SC-related business. The company's wire is used for the onboard superconducting magnets for levitation, guidance, and propulsion of the magnetically levitated trains being tested now at the Yamanashi Test Track. Furukawa also supplies aluminum for the track. Although Furukawa does not appear to be targeting the magnet market, the WTEC team's hosts commented that cryocooled high field magnets (>20 T) and HTS magnets are due to appear early in the next century.

Site: **Hitachi Laboratory, Hitachi, Ltd.**
1st Department of Energy Research
Superconductivity Section
1-1, Omika-cho, 7-chome, Hitachi-shi
Ibaraki 319-12, Japan
http://www.hitachi.co.jp/index.html

Date Visited: June 1996

WTEC Attendees: M. Suenaga (report author), G. Gamota, R. Schwall, R. Sokolowski

Hosts: Dr. Toshiki Iino, Manager, First Department of Energy Systems Research
Kiyoshi Yamaguchi, Senior Researcher
Ryukichi Takahashi, Senior Researcher, Superconductivity Center
Dr. Kazutoshi Higashiyama, Senior Researcher, Superconductivity Center
Katsuzo Aihara, Senior Researcher, Superconductivity Center
Michiya Okada, Senior Researcher, Superconductivity Center

BACKGROUND

Hitachi, Ltd., is one of the largest manufacturing companies in Japan. Its business activities cover a broad area, e.g., electronics, consumer products, large computers, heavy equipment for electric power applications, etc. Hitachi, Ltd., also has a long history of working on applications of superconductors. Its investigation of superconductors started in 1965 at the Central Research Laboratory, and in the late 1960s it constructed what was then a very large (5 MJ) magnet with Nb-Zr-Ti wire for the MITI MHD project. Currently, its activities span from a fundamental study of vortex dynamics by Dr. A. Tonomura (his work is well known), to construction of very large magnet systems, such as for the Large Helical Device at the National Institute of Fusion Science (NIFS) at Nagoya and for the International Thermonuclear Experimental Reactor (ITER). In support of these large construction projects at Hitachi Works, the Superconductivity Center of Hitachi Laboratory conducts relatively small-scale research and development on related subjects, and the center also conducts advanced R&D on materials such as conductor development utilizing high T_c superconductors. Table Hitachi.1 summarizes Hitachi's superconductivity research and development.

Table Hitachi.1
Superconductivity Related Research and Development At Hitachi

Location	Objectives	Related Projects
Advanced Research Laboratory	Vortex Dynamics, Physics	-------
Central Research Laboratory	Superconducting Transistors	ISTEC
	SQUIDs	FED (future electron devices)
	Electronic Applications	
Hitachi Research Laboratory	High T_c Superconductors	ISTEC (SRL)
	Generators	Super-GM (NEDO/MITI)
	SMES	ISTEC
	Fusion magnets	JAERI (ITER), NIFS (LHD)
	Accelerator magnets	KEK (TRISTAN II)
Hitachi Works	Maglev	JR
	Others (High Field, MRI)	(NRIM)
Mechanical Engineering Laboratory	Cryogenic Cooling Systems	-------
Kasado Works	Helium Refrigeration Systems	-------
Hitachi Cable Ltd.	Superconducting Wires	-------
Hitachi Medical Corporation	MRI	-------

SUPERCONDUCTIVITY R&D

As listed in Table Hitachi.1, Hitachi Works is actively involved with a number of large-scale projects in Japan. These include magnet systems for magnetically levitated trains (Japan Railways), a rotor for an electrical generator (Super-GM), a large helical magnet for magnetic confinement of plasma for fusion (NIFS), and coils for a superconducting magnetic energy storage (SMES) system (ISTEC). However, much of the small-scale R&D in support of these large-scale construction projects appears to be over, and very little of the related studies seem to be currently conducted at Hitachi Research Laboratory.

In the area of high T_c conductor development, Hitachi Research Laboratory supports approximately 20 full-time scientific staff in superconductivity, and this personnel level may include a number of staff at Hitachi Cables, Ltd., with whom they work very closely on development of both high and low T_c superconducting conductors. Their excellent work on Tl-1223/Ag and Bi-2212/Ag are well known to the community. During this trip, the WTEC panel also learned that they are developing Nb_3Al multifilamentary wires for the ITER program at the Japan Atomic Energy Research Institute. The highlights from these conductor development programs are given below.

Hitachi Research Laboratory has been devoting itself extensively for a number of years to fabrication of practical conductors utilizing Tl-1223 and is essentially the only group in Japan developing Tl-1223 in a conductor form for magnets and other power applications. In spite of some very interesting work, its earlier efforts at wire making with this system were not successful because of the all-too-familiar weak link problems at grain boundaries in the cuprates, but its most recent results on Tl-1223 tapes are very impressive. Its researchers were able to achieve a J_c of 1.5 x 10^4A/cm^2 with an electric field criterion of 10^{-7}V/cm at 77 K and H = 1 T parallel to the plane of a 1.5 µm thick film. The key to this accomplishment was development of a highly biaxially textured Ag tape by the proper thermomechanical treatment of the Ag substrate. In the best case, Hitachi researchers were able to reduce the f scan full width at half maximum (FWHW) to as low as 6 degrees. On this substrate, the precursor without Tl was first deposited, and then the composite was heat-treated to form Tl-1223 in a Tl_2O atmosphere.

Hitachi's work on the development of high current density Bi-2212/Ag multifilamentary tapes is also well known in the community. Okada and his coworkers have shown earlier that the critical current density of the Bi-2212/Ag tapes can be very high at 4.2 K, i.e., nearly 10^5 A/cm^2 at magnetic fields as high as H = 23 T. More recently, a Bi-2212 coil (49 mm in OD and 12.5 mm in ID) was made to be tested in a 21 T backup field at the High Magnetic Field Laboratory of the National Research Institute for Metals as a part of its 1 GHz Nuclear Magnetic Resonance Facility project. This coil was successfully tested, and it produced 1.76 T in the 21 T backup field, resulting in a total magnetic field of nearly 22.8 T; this suggests that the required magnetic field for a 1 GHz NMR can be produced using a Bi-2212/Ag insert coil at 4.2 K. Furthermore, in a separate study, Hitachi researchers were able to produce a persistent current mode switch that was incorporated with a Bi-2212 magnet. A rate of magnetic field reduction of 0.4%/h was achieved with the switch in operation. Although the switch requires further reduction in joint resistance and improvement in current carrying capacity, the result that they have attained so far is very encouraging for persistent mode operation of a high T_c magnet at low temperature.

In addition to the above high T_c superconductor conductor development, it was interesting to find out that Hitachi has also developed a very high-quality multifilamentary Nb_3Al wire by a jelly roll process, cooperating with Hitachi Cable, Ltd., for fusion magnets such as for the ITER project. The wire has J_c values in the range of 8 x 10^4 A/cm^2 at 12 T, which exceeds the ITER requirement by a comfortable margin. Hitachi researchers have also produced a cable-in-conduit conductor that has carried 20 kA at 12 T. This is impressive. Nb_3Al wire is significantly more difficult to produce than Nb_3Sn wire; however, its mechanical strain tolerance is substantially better than that for Nb_3Sn. Thus, JAERI (Japan Atomic Energy Research Institute) has been encouraging Japanese manufacturers to produce Nb_3Al for the magnets in the ITER project. Earlier, Sumitomo had shown that it is possible to produce practical conductors that can meet the ITER requirement using the jelly roll process. It appears that JAERI is trying to develop other sources for this conductor.

All of the above developments are partially supported by government projects, and this appears to be very important to assure internal funding for these projects. The Tl-1223 work is supported as a part of Super-GM; the Bi-2212 is supported as a part of NRIM's 1 GHz NMR project. However, it is interesting to hear that Hitachi is willing to continue the Tl-1223 work, even though the support from Super-GM will terminate when the project is scheduled to close in a couple of years. This may indicate that Hitachi has confidence in the eventual fabrication of a practical conductor with Tl-1223. The WTEC panel's hosts also think that one of the first commercial applications of high T_c superconductors will be power transformers. Yet, interestingly enough, as far the panel is aware, Hitachi had not been reporting in this area nor other possible areas of applications of high T_c superconductors for electrical utility devices at the time of this WTEC visit.

Site:	**International Superconductivity Technology Center (ISTEC)** **Superconductivity Research Laboratory (SRL)** **10-13, Shinonome 1-chome, Koto-ku** **Tokyo 135, Japan** **http://www.sendai.kopas.co.jp/ISTEC**
Date Visited:	4 June 1996
WTEC Attendees:	J. Willis (report author), D. Gubser, D. Larbalestier, M. Suenaga
Hosts:	Prof. Shoji Tanaka, Vice President, ISTEC, and Director General, SRL Masatoshi Toriihara, Senior Managing Director, ISTEC Dr. Tetsuji Kobayashi, Director, International Affairs Dept., ISTEC Dr. Naoki Koshizuka, Deputy Director General and Director of Div. I, SRL Dr. Yuh Shiohara, Director of Division IV, SRL Hiroshi Irizawa, Director, SRL Planning and Management Dept.

BACKGROUND

In response to the discovery of high temperature superconductivity (HTS), the Ministry of International Trade and Industry (MITI) organized and founded the International Superconductivity Technology Center (ISTEC) in January of 1988 as a consortium of private companies. The ISTEC Superconductivity Research Laboratory (SRL) was established in 1988 in Nagoya and Tokyo as part of a ten-year plan to study HTS. Specific function areas of ISTEC are (1) to perform surveys and studies of the trends in superconductivity technology around the world and to investigate feasibility of industrial applications; (2) to perform basic research and development of HTS at the SRL; (3) to host symposia, workshops, and study meetings and to disseminate information through journal publications; and (4) to promote international exchange by hosting foreign researchers, dispatching Japanese researchers overseas, and hosting workshops and cosponsoring the International Superconductivity Industry Summit (ISIS).

Budget

The budget of SRL comes from two main sources: initial donations (for building and research facilities) and annual fees (for research) from member companies, and contract research funds from the New Energy and Industrial Development Organization (NEDO). The member companies contributed an initial donation of \$47 million in 1988; the level now averages \$6-8 million per year. Contract research from NEDO has increased steadily from \$4.6 million in 1988 to \$23.7 million in FY96. The total FY96 budget was approximately \$32 million[1]. The funding trends are shown in Fig. ISTEC.1. Members also contribute staff, from two to four persons at a time, to work at the ISTEC office or at the SRL.

There are 41 special supporting (full) member companies: 10 are electric utility companies, 10 are in electronics or telecommunications, 6 are electric wire and cable manufacturers, 4 are iron and steel producers, and 11 are from other industries. Of the 41 full member companies, 40 are Japanese companies and one is a U.S. company (DuPont). There are, in addition, 52 ordinary member companies, including six from the United States, which only participate in the information activities of ISTEC.

Organization and Staffing

ISTEC is divided into three departments: General Affairs, Research and Planning, and International Affairs. SRL is divided into two management departments (Planning and Management, and Development Promotion) and nine research divisions: (1) Characterization and Analysis of Fundamental Properties; (2) High T_c

---

[1] Editor's note: Data ISTEC officials provided orally to WTEC staff in the Spring of 1997 indicated that the total FY 1997 budget for SRL would be approximately \$43 million (at ¥120/\$). Comparisons with earlier year funding figures quoted in dollars are complicated by fluctuating exchange rates during this period.

Superconducting Ceramics; (3) Mechanism of Superconductivity; (4) Chemical Processing; (5) Physical Processing; (6) Fundamental Technology for Device Applications; (7) Bulk Processing; (8) High J_c Superconductors; and (9) Database.

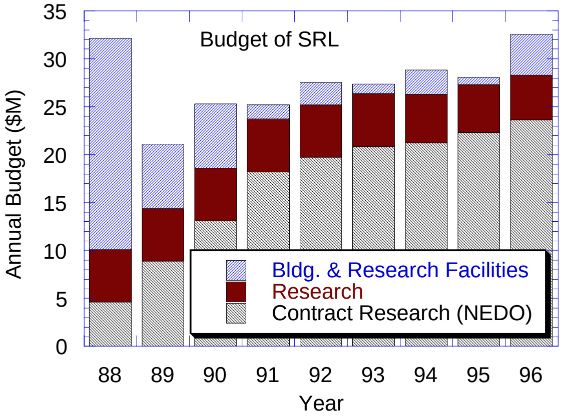


Fig. ISTEC.1. Funding trends for the Superconductivity Research Laboratory.

The main laboratory is located in Shinonome, Tokyo. There are branch laboratories in Nagoya, Tamachi (Tokyo), and Morioka. At the time of this WTEC visit, ISTEC had a total staff of 225, up from 118 in 1988. The staff included 41 administrative staff, 41 students, and 129 researchers, of whom 11 were division directors, 49 were employed by ISTEC, 20 were visiting scientists (most supported by fellowships from the Science and Technology Agency, NEDO, or ISTEC), and 79 had been dispatched from their companies. Member companies pay the salaries for their staff in this last category.

RESEARCH ACTIVITIES

Professor Tanaka summarized the research results of the SRL. The laboratory's main mission is to support materials development for MITI (NEDO) national projects. He stated that there are four major problem areas preventing practical applications of HTS:

1. superconducting tape or wire with $J_c > 10^5$ A/cm^2 at 5 T and 77 K requires improved pinning and elimination of weak links
2. higher magnetic levitation forces and remanent (trapped) magnetic fields in bulk superconductors also require improved pinning and elimination of weak links
3. electronic applications require higher quality thin films
4. all applications require new materials with higher T_c values

The SRL is organized along material technology areas, as listed above. Each of the 9 SRL divisions contributes to solving one or more of the four problem areas. Their solutions will ultimately lead to applications of bulk material (magnetic levitation, flywheels, motors, and bearings), wires (power transmission, generators, superconducting magnetic energy storage (SMES), current limiters, and magnets), and electronic devices. Notable successes highlighted by Prof. Tanaka include growth of large (10 mm) Y-123 single crystals by the crystal pulling method, growth of large RE-123 crystals (Pr, Sm, Nd) by top seeded growth, introduction of Y-211 pinning centers into YBCO in the melt powder melt growth (MPMG) process, introduction of site exchange (Ba and Nd) pinning centers in Nd-123 by thermal processing, and much work on thin film growth techniques.

Bi-2212 and Bi-2223 tapes have not been investigated in the past because (1) they were thought to be too two-dimensional, thus limiting their applicability in high temperature, high field applications, (2) member companies were already pursuing the technology, and (3) SRL was originally allowed to work only in basic and precompetitive R&D areas. SRL is now starting work on textured Y-123 conductors produced by liquid phase epitaxy (LPE). Although Bi-2212 and Bi-2223 tapes are considered to be the most promising materials available for conductor applications, SRL also has begun to focus on the development of next-generation wires and tapes using RE-123.

One unique technology being pursued at SRL is the use of single-crystal Y-123 or Nd-123 as very smooth (approximately 10 Å) substrates for Y-123 thin films for devices. Some of the devices being considered are single flux quantum (SFQ) SQUID logic elements and mixer antennas for communications. To conclude, Prof. Tanaka made some projections of applications for bulk materials and for wire as shown in Figures ISTEC.2 and ISTEC.3.

A short tour of the SRL showed very good support for R&D, including a 400 keV transmission electron microscope, automatic sample-making machine, high field magnet for high pressure NMR, $1 million crystal puller for Y-123, 4 SQUIDS (superconducting quantum interference devices), a rotating anode X-ray machine, and an incredible amount of other equipment. SRL may be the world's best-equipped HTS lab.

PROJECT MANAGEMENT ACTIVITIES

Besides the technical work performed at the SRL, ISTEC is also involved in two large-scale projects (SMES and flywheel), primarily on a project management basis. These projects are both supported by MITI.

SMES Project

Chubu Electric Power Company also plays a major role in managing the technical aspects of the SMES (superconducting magnetic energy storage) project. This project began in 1991 and underwent a midterm evaluation at the end of 1993. At that point, several activities, mostly HTS materials work, were ended. Major activities at the time of the WTEC team's visit were development of the main components (Tohoku Electric Power Co., Chubu Electric Power Co., Electric Power Development Co., Hitachi, Toshiba, Mitsubishi Electric, and Mitsubishi Heavy Industries); system research (Kyushu Electric Power, CRIEPI, Hitachi, Toshiba, and Mitsubishi Electric); and research into measurement techniques and materials evaluation (New Materials Center of the Osaka Science and Technology Center). Work in progress for component development included the evaluation of technology, project planning and production, and testing and evaluation of some prototype components. System studies were examining environmental effects, system optimization, and effects of introduction of SMES on the electric power system. Materials evaluation and experimentation were concentrated on metallic superconductors. This information was obtained from a pamphlet on SMES (ISTEC 1995). In the discussion, the team's hosts stated that Toshiba will be making the toroidal coil and had already produced one of three segments to be built. The original target was 100 kWh. The first coil was at Japan Atomic Energy Research Institute (JAERI) for testing and was to be sent to Lawrence Livermore National Laboratory in the United States for further testing. This is the first case of collaborative international tests for an electric power application of superconductivity to be held between the United States and Japan.

Flywheel Project

The flywheel project is a 5-year program contracted through NEDO that started in 1995. The NEDO brochure shows a five-year target of 10 kWh and 1 m diameter flywheel constructed from fiber-reinforced plastic (FRP). Intermediate flywheels of 0.1 kWh and 0.25 m diameter (steel) and 1 kWh and 0.4 m diameter (FRP) are also planned. One major problem is the insufficient strength of the flywheel material when rotated very rapidly. HTS bulk material will be used for the magnetic bearings, a critical feature to reduce frictional losses and increase overall system efficiency. It seems likely that SRL will contribute with HTS materials work.

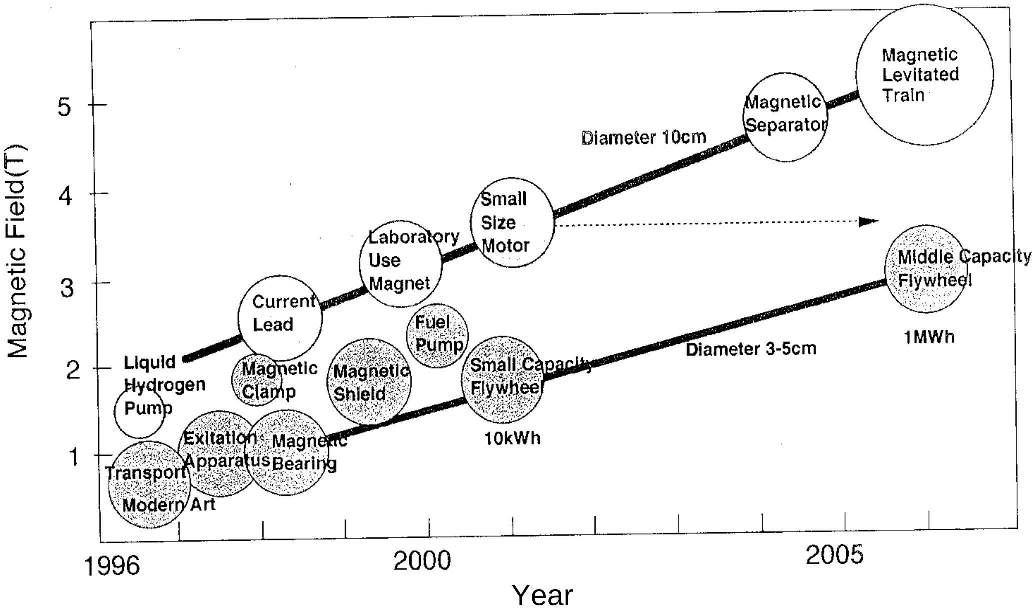


Fig. ISTEC.2. Projections for technology development of bulk HTS applications.

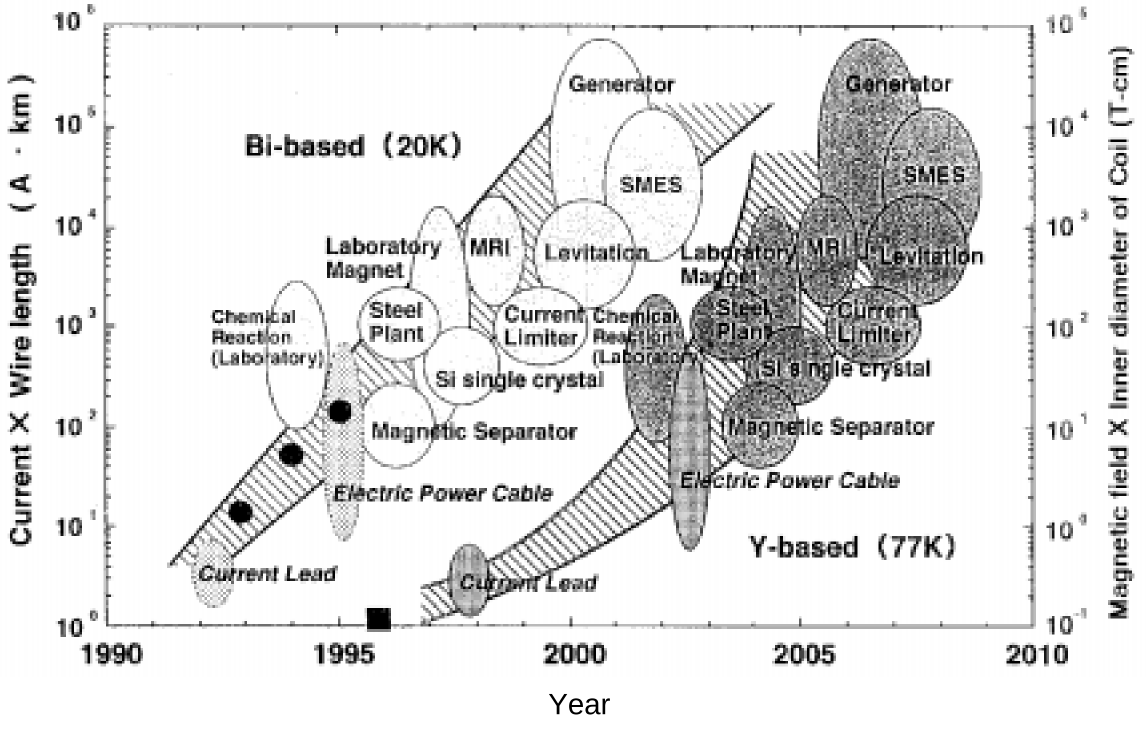


Fig. ISTEC.3. Projections for technology development of HTS wire applications.

FUTURE OF ISTEC

ISTEC was established in 1988 and at the time of this WTEC visit was being reviewed during its eighth year by academic, industry, and government committees. Discussions seemed to suggest that ISTEC will be extended for another 5 or 10 years but with some changes possible in organization, major goals, etc.

Government Funding

Mr. Toriihara gave a presentation on governmental funding of HTS, future prospects, and how the system in Japan differs from that in the United States and Europe. Table ISTEC.1 shows the FY95 and FY96 budgets for Japan. Table ISTEC.2 shows the breakdown of funding for MITI projects. These are dominated by Super-GM and other materials development work, such as that carried out at ISTEC through NEDO. Cuts in some projects near completion (Super-GM) are offset by increases in materials R&D.

On November 15, 1995, the Japanese government adopted the Science and Technology Basic Law (Law No. 130 of 1995). This law

- sets guidelines for the promotion of science and technology
- sets responsibilities of the national and local governments in promoting science and technology
- provides for formulation of a basic plan for science and technology and securing of funds to carry out the plan
- states that the nation shall promote balanced support of diversified R&D, obtain and train researchers and technicians, improve research facilities, promote information-intensive research, and promote R&D exchanges

The basic plan is the most important part of the law, and it was to be formulated before the end of June 1996, in consultation with a nongovernmental panel of experts. This new law is expected to be beneficial to the further development of superconductivity R&D.

Figure ISTEC.4 shows a comparison of U.S. and Japanese government support for superconductivity. The large increase and then decrease in the U.S. budget, particularly for procurement, is dominated by the run up to and cancellation of the Superconducting Super Collider (SSC) project. The trends seen here indicate a continuing strong government support for superconductivity in Japan. Also, the government of Japan has recently started large new funding projects for universities through both MITI and STA. (Note: This was discussed in great detail by Prof. Kitazawa at Tokyo University during the June 7 site visit.)

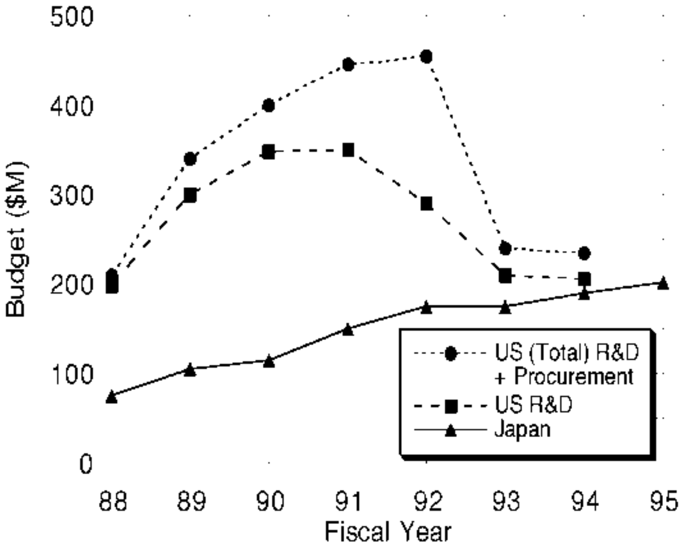


Fig. ISTEC.4. Comparison of U.S. and Japanese government budgets for superconductivity.

Table ISTEC.1
FY95 Budget and FY96 Draft Budget Figures for Superconductivity R&D (in $ millions)

Ministry Agency*	Themes	1995 Budget	1996 Budget
MITI	Industrial Science and Technology R&D; New Sunshine Project, SMES, Flywheel Storage	94.45	107.21
STA	Superconducting Materials Multicore Project; Fusion research, etc.	49.19†	34.51†
MOE	Maintenance of Superconductivity Related Educational System	11.92	12.61
MOT	Support for MAGLEV	48.26	45.40
MPT	High Speed, High Efficiency Communication Technology R&D as part of the Electrical Communications Frontier R&D Project	1.18	1.26
Total		**205.00**	**200.99**

* Key to Ministries/Agencies: MITI-Ministry of International Trade and Industry; STA-Science and Technology Agency; MT-Ministry of Transport; MOE-Ministry of Education; MPT-Ministry of Posts and Telecommunications.

† In addition to this budget, partial funding has been allocated from the science and technology promotion expenses, etc.

Source: *ISTEC Journal* 9 (1) 1996 (February), Japanese Edition.

Table ISTEC.2
FY95 and FY96 Superconductivity Budget for MITI (in $ millions)

Topic	FY95 Budget	FY96 Draft	Notes	Time Period
1. R&D of Superconducting Materials, Devices, etc.	**38.09**	**59.75**		
A. R&D of Industrial Science & Technology; Superconducting (SC) Materials & Devices	31.95	33.39	Development of SC materials and devices	FY88-97
B. R&D of SC Material Manufacture in Microgravity	5.80	26.02	Development of SC materials utilizing space environment	FY91-01
C. National Laboratories; Special Research Projects	0.34	0.34		
2. Development of Electric Power Applications Technology	**54.36**	**45.45**		
A. New Sunshine Project; Electric Power Applications Technology	42.36	28.76	Superconducting Generator, etc. (Super-GM)	FY88-98
B. Developmental Study of Elemental Technologies for an SC Energy Storage System	8.90	11.50	Development of technology for a SMES system	FY91-98
C. R&D of SC Flywheel Energy Storage System	3.10	5.20	Development of elemental technology for a practical HTS flywheel	FY95-99
3. Survey of Superconductivity	**2.00**	**2.00**		
A. Development of SC Materials for Generators, etc.	2.00	2.00	Trend survey on development of rare earths and other materials required for HTS	FY88-97
Total	**94.45**	**107.21**		

Note: In addition to the above, R&D on biomagnetic systems will be conducted by the Superconducting Sensor Laboratory; funding will be provided by the Japan Key Technology Center.

Source: *ISTEC Journal* 9 (1), 1996 (February), Japanese Edition.

In a comparison of superconductivity R&D in Japan and the United States, Japan is seen as having good government support and a unique research laboratory specializing in HTS (SRL), but the R&D is mostly conducted by large companies so that the development of applications for small markets is rare, and basic research is weak in the universities and national laboratories. In the United States, the existence of a defense market is seen as a driver for procurement of applications, and venture companies are very common, allowing exploitation of many markets large and small. On the negative side, U.S. government policy is seen as unstable, and large companies show little interest in HTS.

Market Forecast

ISTEC is a member of the International Superconductivity Industry Summit (ISIS), and prepares budget estimates for the superconductivity market in Japan. Table ISTEC.3 lists the ISIS predictions presented at the 5th International Superconductivity Industry Summit (ISIS), held at Hakone, Japan, in May 1996. Fig. ISTEC.5 displays the predictions graphically. Note that sales in the developing world, although not shown explicitly in the table and figure, are predicted to be equal to the total of those in the United States, Japan, and Europe.

Table ISTEC.3
1996 ISIS Forecast of Sales Opportunities in Respective Regions (U.S. $ Billion)

Region Year ⟶	**1995**	**2000**	**2010**	**2020**
United States (CSAC)		4.6	18	62
Europe (CONECTUS)		1	3	18
Japan (ISTEC)		2	16	42
Total for US, EU, Japan	1.7*	7.6	37	122
Total for entire world†		15.2	76	244

* Commercial sale of MRI and other magnets only.

† This forecast includes the expected expansion of sales by 100% into developing countries as predicted by the World Bank.

Sources: Estimates were made by the Council on Superconductivity for American Competitiveness (CSAC) for the U.S., the Consortium of European Companies Determined to Use Superconductivity (CONECTUS) for Europe, and the International Superconductivity Technology Center (ISTEC) for Japan; also, ISIS 1996.

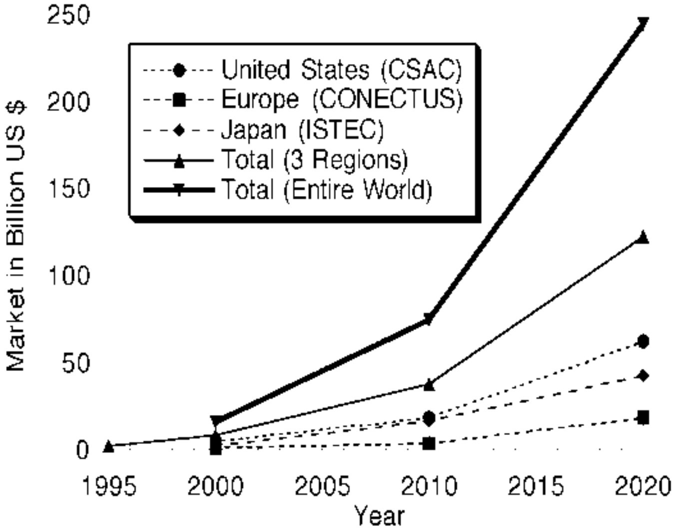


Fig. ISTEC.5. Prediction of regional and world markets for superconductivity by the 5th International Superconductivity Industry Summit (ISIS 1996). Sales in the developing countries typically equal those in developed countries (U.S., Europe, Japan), according to the World Bank.

REFERENCES

ISIS. 1996. The 5th international superconductivity industry summit (ISIS-5) communiqué (May). Attachment: Figure 1 and Table 1. Tokyo: ISTEC.

ISTEC. 1996. *SMES: Research of elemental technologies for development of SMES system.* Tokyo: ISTEC.

Tanaka, S. 1997. A way to commercialization of high-T_c superconductors. In *Proc., 16th Int'l. Cryogenic Engineering/Int'l. Cryogenic Material Conf.* Kitakyushu, Japan, 20-14 May. Oxford: Elsevier Science.

Site:	**Kobe Steel, Ltd.** **Kobe Corporate Research Laboratory** **Electronics Research Laboratory** **1-5-5, Takatsukadai, Nishi-ku** **Kobe 651-22, Japan** **http://www.kobelco.co.jp/indexe.htm**
Date Visited:	6 June 1996
WTEC Attendees:	J. Willis (report author), D. Gubser, D. Larbalestier, M. Suenaga
Hosts:	Dr. Takefumi Horiuchi, Senior Technical Director, Electronics and Information Division Dr. Rikuo Ogawa, General Manager, Electronics Research Lab. Dr. Yoshio Kawate, Director, Electronics Research Laboratory Kazuo Takabatake, General Manager, Electronics and Information Div., and President, Japan Magnet Technology Dr. Masao Shimada, Manager, Superconductivity Research Section (now Manager, Advanced Products Development Ctr., Technical Development Group, Kobe Steel) Dr. Seiji Hayashi, Senior Researcher, Superconductivity Research Section Dr. Takayuki Miyatake, Senior Researcher, Superconductivity Research Section Ryoichi Hirose, Senior Researcher, Superconductivity Research Section Dr. Kazuyuki Shibutani, Researcher, Superconductivity Research Section Dr. Yoshito Fukumoto, Researcher, Superconductivity Research Section

BACKGROUND

Kobe Steel is a large (19,400 employees in 1994), diversified company founded in 1905. It has four primary product areas: (1) iron and steel, (2) aluminum and copper, (3) engineering and machinery, and (4) electronics and information technology. Long-range corporate goals call for maintaining steel as the core business. Kobe Steel expects the aluminum and copper and the machinery sectors to provide a broad base for growth. The goal for the electronics and information sector is to expand into semiconductors, factory automation, and robotics.

Net sales for the years ending 31 March 1994 and 1995 were \$10.68 billion and \$10.66 billion, respectively, for operating incomes of \$359 million and \$571 million for the same periods. For those years, the company recorded net losses of \$10 million and \$957 million, respectively. The losses reflect weak economic conditions due to Japan’s recession, the appreciation of the yen, and the severe damage to production facilities, housing units, and corporate headquarters caused by the Great Hanshin Earthquake, which struck Kobe in January 1995. Product sector sales are iron and steel (45%), aluminum and copper (22%), and machinery, engineering, and electronics (33%). This latter sector has been showing the strongest growth. The Kobe Steel Group has over 70 overseas subsidiaries and affiliates in the United States, Europe, and Asia. Kobe Steel has a joint venture with USX in Ohio (USS/Kobe Steel Co.) to produce various steel products and a joint venture with Texas Instruments (KTI Semiconductor, Inc., located in Japan) that produces 9,000 8-in. silicon wafers per month.

CORPORATE LABORATORY ORGANIZATION

Besides the four main business divisions listed above, there is a Technical Development Group primarily located at the Kobe Corporate Research Laboratories at Seishin Industrial Park in western Kobe, at which a total of about 1,000 employees work. This laboratory is divided into five research laboratories: (1) Materials, (2) Mechanical Engineering, (3) Chemical, Polymer, and Biotechnology, (4) Process Technology, and

(5) Electronics. The Superconductivity Research Section is one of seven research areas within the Electronics Research Laboratory.

SUPERCONDUCTIVITY

Kobe Steel established its first superconductivity and cryogenics laboratory in 1964. In 1985 there was a major reorganization of the corporate laboratories, and these activities were dispersed into the Mechanical Engineering, Materials, and Electronics Research Laboratories. When high temperature superconductivity (HTS) was discovered, the researchers were collected into the newly established Superconductivity and Cryogenics Technology Center. Major business products at this time were Nb-Ti and Nb_3Sn superconductive wire and helium liquifiers. Finally, in 1994 in another reorganization, these functions became the present day Superconductivity Research Section of the Electronics Research Laboratory.

The Superconductivity Research Section is divided into three groups:

1. the Wire Group, which works on metallic superconductive wire
2. the Magnet Group, which performs R&D on superconducting magnets, mostly nuclear magnetic resonance (NMR) magnets
3. the Applications Group, which works on HTS materials, cryogenics, novel magnets, and new applications

HTS Research Topics

The logical progression of development is seen as R&D → Products → Markets. There is an established and expanding market for NMR magnets, which require wire, magnets, and cryostats. The goals for these products are to improve the performance of the system and reduce the cost. New markets being explored are cryogen-free “dry” magnets and novel testing equipment, such as the watermelon magnetic resonance imaging (MRI) system. Work on HTS materials is directed toward current leads for the dry magnets and coil inserts for high frequency (high field) NMR magnets. This research is concentrated on Bi-2212, because the application is at 4.2 K, and high J_c, high “n value” ($J = E^n$, where J is the current density and E is the electric field), and thus low loss, wires are easier to make from this material than from Bi-2223. To increase the strength of the (round) wire to withstand the large Lorentz forces at high magnetic fields, multifilamentary wire is being produced. The first stack of wire uses pure silver for chemical compatibility with the Bi-2212, but this is then put into an outer tube of silver alloyed with Ni and Mg in what is called “double sheath” wire. A small coil has been produced this way and has generated a field of 0.2 T in a background 21 T field. A persistent current switch is also being developed for monofilament Bi-2212 wire. At present, a coil generating 0.1 T shows a decrease of ~90% in the magnitude of the trapped magnetic field in the first 10 minutes after the persistent switch is closed; after that it is very stable. Such a device would be required in a 1 GHz NMR system.

Superconductivity Business Strategy

Kobe Steel’s business activities related to superconductivity largely take place through Japan Magnet Technology (JMT), a joint venture between Kobe Steel and Magnex, a magnet-making company in the U.K. Business opportunities being considered relate to energy, transportation, NMR, and others. All but NMR are mostly large-scale, requiring substantial R&D funds. “Large-scale” usually means R&D as part of a national project, but these are unpredictable in the long term (and Kobe Steel has never been interested in the Maglev train or the SSC). Kobe Steel and JMT are taking a wait-and-see attitude on this type of project. The NMR and MRI markets are of medium size and mature, so there is much competition for magnets < 4 T. Kobe’s future target area is high field NMR systems (750 MHz [=17.6 T] and higher), which also require a continuous R&D investment. The strategy is to sell wire and lower field NMR and MRI magnets to support the high field NMR magnet research. Product sales also allow Kobe Steel to maintain an R&D base to prepare for future large-scale business opportunities.

Kobe Steel began producing Nb-Ti wire in 1973 and Nb_3Sn wire in 1983. In 1984 it built a 1 MJ SMES and a high field resonance magnet. In 1990, it established JMT, the joint venture with Magnex. In 1993, Kobe Steel began making high "n-value" Nb_3Sn by the bronze process. In 1994, JMT delivered the world's first 750 MHz magnet to Pennsylvania University. In 1995 Kobe Steel developed the watermelon MRI system. Kobe Steel currently has about 50% of the Nb_3Sn wire market for NMR systems (Vacumschmelze has the rest). In 1995, 100% of the magnets for the NMR systems sold by JEOL, Ltd., were produced by Kobe Steel and JMT; some magnets were also sold to the other two producers of NMR systems. The target for 1996 was an 800 MHz magnet. JMT management would also like to produce magnets for the "NMR Park" proposed by the Science and Technology Agency (STA).

Table Kobe.1 shows the annual output of Kobe Steel, JMT, and Magnex, and their technical contributions. NMR magnets presently produced by JMT and Magnex are 300, 400, 500, 600, and 750 MHz. In planning stages at the time of the WTEC visit were magnets of 800, 850, 900, 950, 1,000, and 1,050 MHz. Magnets above 900 MHz will require HTS insert coils to attain the high fields.

Table Kobe.1
Kobe Steel and Affiliates Superconductor Business:
Ownership, Products, Production, Sales, and Technical Contributions

Business Unit	Kobe Steel Share (%)	Product	Units/Year	Value ($ millions)	Technical Contributions
Kobe Steel	100%	Nb-Ti / Nb_3Sn wire	50/10 tons	10	All R&D on wire, magnets, HTS and wire products
JMT	87%	high field NMR	100	13	Magnet production and development, primarily high field NMR magnets
Magnex	25%	MRI, NMR	100	25	MRI (up to 9 T) and NMR magnets
Total				**48**	

In addition to the products listed in Table Kobe.1, Kobe Steel is developing new markets such as that for its dry magnet, which is estimated to be 15-20 units per year in Japan. Figure 4.20, p.57, shows the first page of an advertisement for this magnet. Kobe's 10 T 100 mm bore entry in the field is unique in that it is rotatable from a vertical to a horizontal bore. It uses a Nb-Ti/Nb_3Sn magnet and Bi-2223 current leads to reduce the heat leak. HTS current leads are also applicable to NMR and MRI magnets. Growth areas for MRI magnets are for cryogen-free and open (split magnet) systems.

Another new market area is "watermelon MRI." There is a real market in Japan for this product, where a watermelon typically costs $30 and the consumer wants to be sure he is getting a good one. The technology was developed for the Japan Farmers Union to detect voids and measure sugar content to assess quality and ripeness. The system developed can examine a melon for voids in 1 s and assess the sugar content in 6 s using sophisticated NMR pulse techniques. Figure Kobe.1 shows the apparatus and scans of a good and a defective melon. The characterization adds an additional 1.5¢ to the cost of a melon, prorated over the eight-year life of the equipment. Kobe Steel expects orders for four to six of these units per year at a price of approximately $1.0 million each.

Kobe Steel and JMT hope to develop markets for 1 GHz and higher NMR magnets and a custom made cryocooled (at over 20 K) superconducting magnet over the next 20 years.

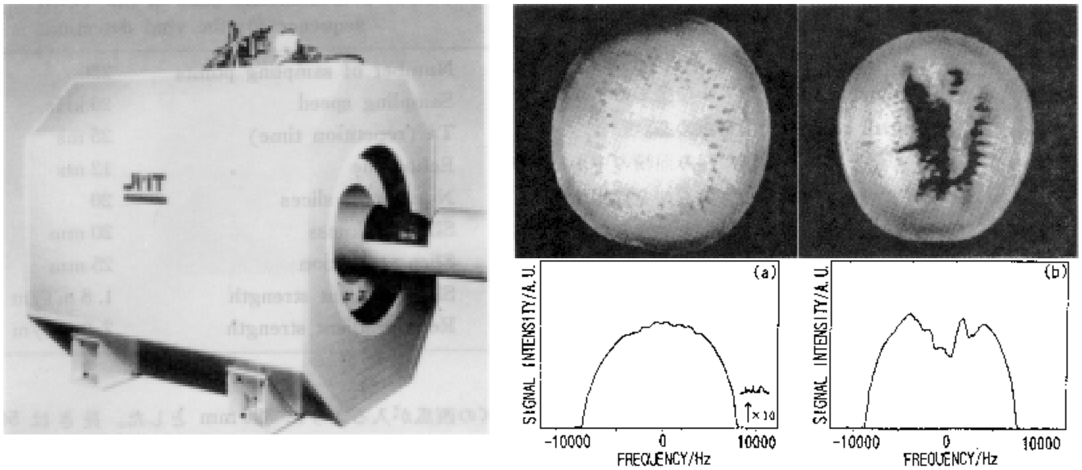


Fig. Kobe.1. MRI system for determining void and sugar content of watermelons. Scans of a good (a) and a defective watermelon with voids (b).

On a short tour, the WTEC team saw some of the HTS work on double sheathed Bi-2212 wire, persistent current switches, and insert magnets. Team members also saw the watermelon MRI analyze a set of watermelons in real time and surprisingly rapidly. Several employees were winding magnets, both in a room for that purpose and, because of limited space and expanding demand, out on the main floor. A recently assembled 750 MHz magnet was quite compact compared to others available commercially.

Personnel

Staffing has been increasing in recent years by the addition of part time employees. R&D work is performed by 20 persons, 5 for HTS and 15 for LTS. Wire production (Kobe Steel) has 20 permanent and 25-30 part-time workers. Magnet production at JMT had 20-25 permanent employees and an extra 25 in June 1996. Thus there are a total of about 120 employees working on superconductivity at Kobe Steel and JMT.

Conductor and Materials Development

Kobe Steel is doing R&D on Nb-Ti, bronze process Nb_3Sn, and Bi-2212. Its most significant contribution to HTS conductor development is achievement of high strength and high critical current density by development of double (Ag-alloy/Ag)-sheathed Bi-2212 conductors for solenoid coils. Major technical challenges are seen to be achievement of homogeneous microstructures over long lengths, superconducting joints, and persistent current switches. Current Bi-2212 multifilament conductor properties are $J_c > 10^5$ A/cm^2 and $J_e > 5 \times 10^4$ A/cm^2 at 4.2 K and 0 T; I_c x L = 13.4 kAm (4.2 K, 0.4 T) for rectangular wire, and 57.2 kAm (20 K, 1 T) for tape.

Generation and Storage, Transmission, and Distribution

Kobe Steel has no direct activities in this area; however, it has been a member of the Super-GM project. The major contribution of Kobe Steel to this project is the research and development of Nb_3Sn superconducting wire for ac use. Kobe Steel specializes in powder metallurgically processed Nb_3Sn wire as one of the candidates.

End User Applications

This primarily means high field NMR magnets and, to a smaller extent, cryocooled magnets and other new applications. Some work is being done in collaboration with external organizations, such as the National Research Institute for Metals (NRIM) and the Institute for Metals Research at Tohoku University. Work is primarily on a collaborative, no-funds-exchange basis.

Kobe Steel anticipates an end user market for HTS materials in 20 K cryocooled magnets and very high field (>850 MHz) NMR magnets. There is no competition from LTS systems in these areas. Kobe management expects commercialization for high field superconducting magnets, such as a 1 GHz NMR magnet, a 1.5 GHz NMR magnet, and a custom made cryocooled (at over 20 K) superconducting magnet, to take place in 5, 10, and 20 years, respectively. Other new markets for magnets will be for LTS and HTS cryocooled magnets, split MRI magnets, cryocooled HTS MRI magnets, HTS + LTS NMR magnets for >850 MHz, and novel applications (such as the watermelon MRI).

Site: **Mitsubishi Electric Corporation (MELCO)**
Advanced Technology R&D Center
8-1-1, Tsukaguchi-Honmachi
Amagasaki City, Hyogo 661, Japan
http://www.melco.co.jp:80/index_e.htm

Date Visited: 6 June 1996

WTEC Attendees: R. Schwall (report author), R.D. Blaugher, J. Daley, G. Gamota, P. Grant, H. Morishita, R. Sokolowski

Hosts:
Dr. Ken Sato, General Manager, Electromechanical Technology Lab
Shiro Nakamura, Deputy Manager, Electromechanical Systems Department
Hisao Watarai, Manager, Metal and Ceramics Technology Department
Dr. Mitsunobu Wakata, Manager, Superconducting Materials Group
Dr. Hideto Yoshimura, Manager, Cryogenics and Superconductivity Group
Dr. Kazuyoshi Kojima, Strategic R&D Planning Group

BACKGROUND

The history of the MELCO effort in superconductivity can be traced back to the early 1960s when work began worldwide on high field Type II superconductors. MELCO currently maintains an active program in many areas of superconductivity. Figure MELCO.1 shows distribution of personnel by project area.

The WTEC team's visit was to the Advanced Technology R&D Center, which has approximately 600 researchers and 150 support personnel. Figure MELCO.2 gives the center's top-level organization.

The superconductivity effort is divided between three laboratories. Coil research is in the Electromechanical Technology Laboratory, conductors research is in the Metals and Ceramics Technology Department of the Materials Technology Lab (which is physically located at the Sagami Administration Center), and electronic devices are pursued in the Advanced Devices Technology Lab.

SUPERCONDUCTING MATERIALS

Nb_3Sn for ITER-CS Model Coil

The CS model coil for the International Thermonuclear Experimental Reactor (ITER) is a 13 T pulsed magnet and requires Nb_3Sn strands with high J_c and low hysteresis loss. MELCO uses an internal tin process and has successfully manufactured 600 km (2.75 tons) of strands. At the present time Nb_3Sn conductor is not a production business for MELCO, and the conductor group is exploring high field NMR and refrigerated magnets as markets for the conductor technology. Continuing research focuses on increasing J_c and decreasing cost.

HTS Materials

MELCO has halted the development and production of long lengths of HTS conductor and has focused resources on the search for a strong pinning system without weak links and on processing for the Bi system. Issues mentioned relative to the Bi system were process development to increase filament density and improve preferential orientation of individual crystals.

Research continues on HTS current leads, and MELCO researchers have produced (Bi, Pb)-2223 current leads with J_c(77 K, 0T) of about 10 A/mm^2; the target at the time of the WTEC visit was 100 A/mm^2 with high mechanical strength.

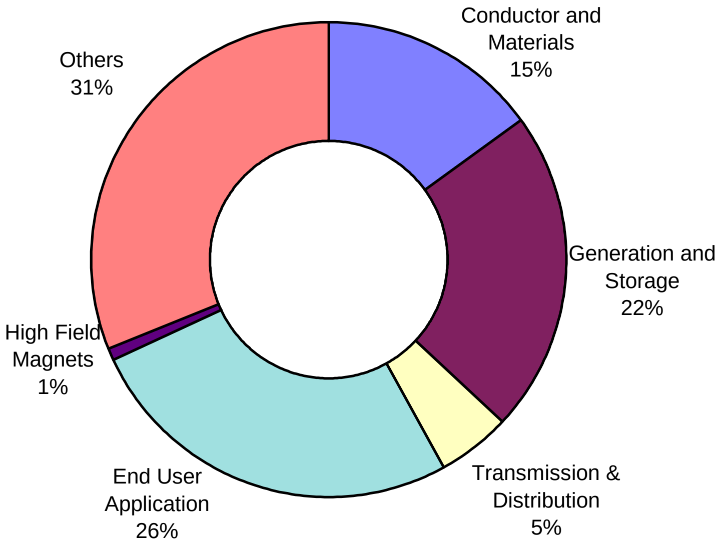


Fig. MELCO.1. Percentage of R&D manpower resources.

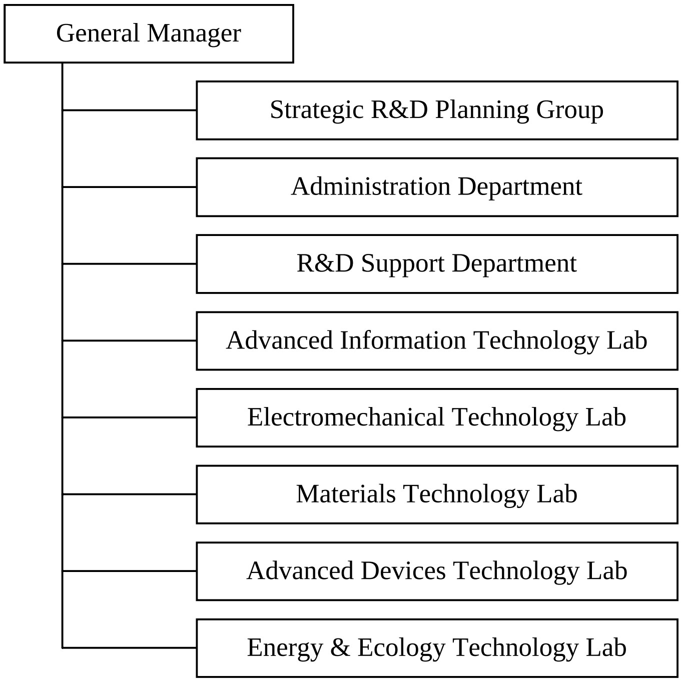


Fig. MELCO.2. Advanced Technology R&D Center.

EQUIPMENT

Generators

MELCO has been working on superconducting generators since 1971. It participated in a Ministry of International Trade and Industry (MITI) 6 MW program from 1974 to 1976, and a MITI 30 MW program from 1977 to 1982, and is currently participating in the Super-GM program, which has a duration of 10 years. The WTEC team's hosts stated that the only realistic application of the present 70 MW system would be stabilization of the power grid. Given the very competitive nature of the worldwide generator business, MELCO management will find it very difficult to economically justify generator R&D with internal funding after completion of the government program.

Transformers

The panel's hosts at MELCO indicated that they feel the projected costs for HTS transformers are too high to be commercially successful. If the prices can be made competitive, their opinion is that reduced weight is the largest advantage for the Japanese market.

SMES

MELCO is participating in a program with KEPCO targeting 400 kJ Nb_3Sn coils. Three coils made by three different companies have been installed and tested this year.

Flywheels

MELCO has completed a 100 W-hr system as part of a Shikoku Electric Power Company (SEPCO) program. The flywheel is alloy steel in a stainless jacket. The bearing features a rotating magnet and a stationary YBCO element operating in liquid nitrogen. MELCO is also participating in a MITI/NEDO study on flywheels that is reported and covered in more detail in the NEDO and ISTEC reports.

MRI Magnets

MELCO produces magnets for MRI systems marketed by Shimadzu. It currently produces a magnet with zero helium consumption, and it has about 50 of these in the field. The refrigerator is a three-stage Gifford McMahon (GM) with a $Ho_{1.5}Er_{1.5}Ru$ regenerator developed by Mitsubishi Materials.

Cryogen-Free Magnets

MELCO is active in this area and has completed a Klystron magnet that operates at 3.8 K with a GM refrigerator. Its largest low-temperature GM machine produces 2.2 W at 4.2 K.

Synchrotron Ring

MELCO has produced a synchrotron ring for industrial research such as X-ray lithography and is currently using it for development of the 1 Gbit memory chip. It would produce such rings if a commercial market developed.

MAGLEV Refrigerators

At the time of the WTEC visit, the heat load on MELCO's MAGLEV magnets was 5 W static and 3 W due to induced currents during operation.

Site:	**National Laboratory for High Energy Physics (KEK)** **Research Cooperation Division** **1-1 Oh'ho, Tsukuba-shi** **Ibaraki-ken 305, Japan** **http://www.kek.jp/**
Date Visited:	5 June 1996
WTEC Attendees:	R. Schwall (report author), R.D. Blaugher, J. Daley, G. Gamota, H. Morishita, R. Sokolowski
Hosts:	Yoshitaka Kimura, Vice Director Dr. Takakazu Shintomi, Professor Dr. Hiroshi Morita, Professor Dr. Akira Yamamoto, Professor Dr. Kiyosumi Tsuchiya, Professor Dr. Shinji Mitsunobu, Professor Dr. Kenji Hosoyama, Professor Dr. Shuichi Noguchi, Professor Dr. Eiji Ezura, Professor

BACKGROUND

The National Laboratory for High Energy Physics (KEK) was established in 1971 as the first Interuniversity Research Institute under the Science Council of the Ministry of Education, Science, and Culture (Monbusho). Its purpose is experimental research in elementary particle physics and other related studies. Its principal accelerators are a 12 GeV proton synchrotron, 2.5 GeV electron accelerator, and 30 GeV electron positron collider (TRISTAN). In addition to high energy physics, extensive studies of material and life science are executed with these accelerators.

In FY 1994 the budget totaled ¥27,228 million, of which ¥4,924 million was for salaries, ¥20,306 million for operating costs, and ¥1,998 million for capital improvements. The laboratory has about 650 total staff, of which about 540 are technical personnel.

SUPERCONDUCTIVITY PROGRAM

At the time of the WTEC visit, KEK had a limited program in HTS but wide-ranging efforts in applications of superconductivity to high energy physics. Of particular note is the extensive work in large helium cryogenic systems. The program is characterized by collaborations worldwide, and KEK representatives presented a very complete and helpful overview of those programs to the visiting WTEC team. A summary of the programs follows.

Magnet R&D for LHC

A CERN-KEK cooperation has been established for basic R&D on high field dipoles and the development of insertion quadrapoles. The dipole work is complementary to that at CERN, and a 50 mm single aperture short model has reached 10.3 T. The insertion quads for the two insertion regions will be developed in Japan; a design study for the model magnets was underway at the time of the WTEC team's visit. The first model magnet was to be constructed in 1996, two additional model magnets were to be constructed in 1997, and two prototype magnets were to be completed by 1998. Production of the insertion quads is to start in 2000, with 16 magnets to be completed by 2002.

Magnet R&D for KEKB B-Factory

The next major accelerator to be commissioned at KEK is the KEKB B-Factory. Work in superconductivity and cryogenics is centered on four tasks:

1. layout of the interaction region
2. compensation solenoid
3. final focus quadrapole
4. cooling system

Significant and detailed results on all four areas were presented to the WTEC team, and this work has been well documented in the high energy physics literature. Of particular interest to the team was the detailed experience with the cryogenic system for the TRISTAN superconducting rf cavities over a seven-year period from October 1988 to June 1995. The detailed failure analysis on this system is perhaps one of the most complete available on any large cryogenic refrigeration system.

Detector Magnet R&D

KEK has constructed and used a series of ever more sophisticated detector magnets since 1984. These magnets are particularly challenging because of the simultaneous and conflicting requirements for high magnetic field, a highly transparent winding and cryostat, high mechanical strength, and high thermal stability.

The design approach at KEK has involved using aluminum-stabilized Nb-Ti conductor, very thin windings (often with no bobbin), and conduction cooling from the ends of the coil to eliminate the less transparent components of the cryostat. Table KEK.1 gives a historical listing of the coils fabricated to 1996 and those that are planned. Details on each magnet have been published in the technical literature.

LTS Superconducting Cavity Development

KEK is engaged in a variety of R&D projects on superconducting cavities made of Nb. These cavities were used on TRISTAN and will be used on the KEK B-Factory. KEK, in collaboration with CEBAF, has developed relatively low-cost reliable methods for fabricating high Q, high gradient, accelerator cavities. Again, the technical details have been published by the KEK group.

HTS Cavity Development

The only currently active HTS project at KEK is an effort to measure the microwave properties of HTS films with the intent to apply them to accelerating cavities for future high energy physics machines. This work, in collaboration with NRIM and selected commercial companies that prepare the HTS films, involves measuring the surface resistance of films at 3 GHz and 13 GHz. The measurements are accomplished by fabricating a copper cavity with provision for mounting a HTS film in one end (Fig. KEK.1). The surface resistance is inferred by measurement of the cavity properties with a network analyzer; hence, the fields at the HTS film are rather low.

Table KEK.1
Superconducting Solenoids for Collider Experiments

Experiment	Lab	Year	B (T)	D coil (m)	X (Rad. L)	E/M (kJ/kg)	Technical Remarks
Cello	Saclay/Desy	1978	1.5	1.7	0.5	?	Soldered Al stab. S/C Indirect 2-phase He cooling
TPC	LBL/SLAC	1983	1.5	2.2	0.75	?	Cu-stabilized, quench-back by 2nd coil
Cleo	Cornell	1981	1.5	2.1	0.75		
CDF	Tsukuba/Fermi	1984	1.5	3.0	0.84	5.4	Coextruded Al-stab.
Topaz	KEK	1984	1.2	2..9	0.70	4.3	Inner coil winding
Venus	KEK	1985	0.75	3.5	0.52	2.8	CFRP vacuum shell
Amy	KEK	1986	3.0	2.5	—		Cu/Al stab., pool boiling
Cleo-II	Cornell	1988	1.5	3.1	2.5		
Aleph	Saclay/CERN	1987	1.5	5.5	2.0	5.5	Thermo-siphon cooling
Delphi	RAL/CERN	1988	1.2	5.6	4.0		
H1	RAL/CERN	1990	1.2	5.6	1.2	4.8	LHe-pump cooling
Zeus	DESY	1988	1.8	(2)	0.9	5.5	
SDC* (R&D)	KEK/Fermi/SSC	1993	(>2)	3.7	1.2	9.6	High-st. Al-stab. conductor, Pure-Al strip technique for quench protection
Belle	KEK						
Dϕ	Fermi						
Atlas*	KEK/CERN		2.0	2.5	0.8	8.5	(planned)
CMS	Saclay/CERN		4.0	3.2			(planned)

* Air core solenoid; D-bore = D-coil — 0.2 m, typically

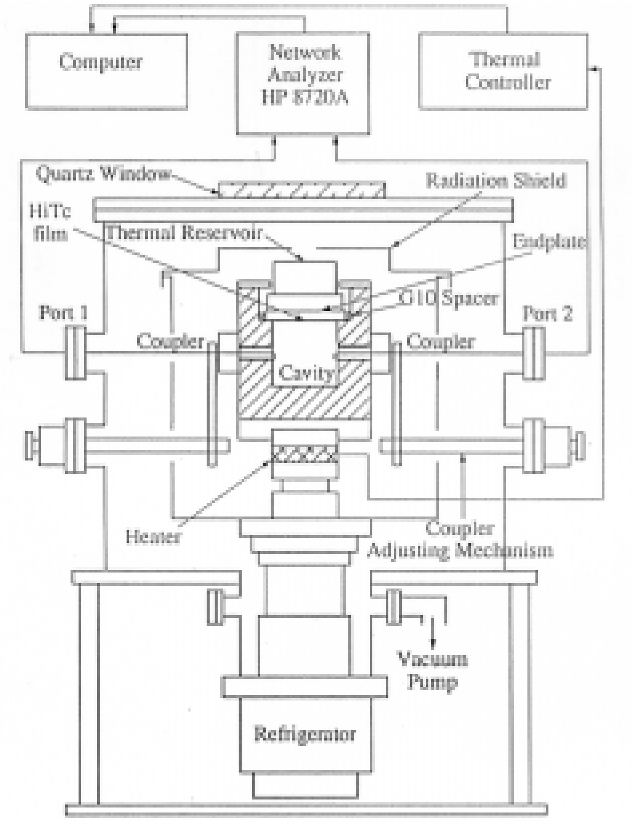


Fig. KEK.1. Experimental set-up of surface resistance measurement.

Site:	**National Research Institute for Metals (NRIM)** **1-2-1, Sengen, Tsukuba-shi** **Ibaraki 305, Japan** **http://www.nrim.go.jp/**
Date Visited:	5 June 1996
WTEC Attendees:	R. Sokolowski (report author), R.D. Blaugher, J. Daley, P.M. Grant, H. Morishita, R. Schwall, J. Willis
Hosts:	Dr. Kazumasa Togano, Director, 1st Research Group (Superconducting Materials) Dr. Hitoshi Wada, Research Dir., Tsukuba Magnet Laboratories

BACKGROUND

The National Research Institute for Metals (NRIM) was established forty years ago as an organization attached to the Science and Technology Agency (STA). Of the 450 people working at the two NRIM campuses (Tsukuba and Sakura), 300 are active researchers; the balance provide administrative and other support functions. NRIM's overall research budget for fiscal 1996 was approximately ¥3.9 billion. The budget for superconducting materials, which represents about one-third of the total research budget of NRIM, grew from ¥1.38 billion in 1993 to ¥1.63 billion in 1995. The weakening of the dollar from ¥122 to the dollar in 1995 to ¥105 in 1996 exaggerates this growth when expressed in dollars ($11.3 to $16.3 million). STA conducts an annual review of NRIM activities, but there is no industrial oversight committee such as the one that oversees progress at the DOE laboratories; consequently, there is no evaluation of the commercial worth or applicability of NRIM research, although the work done is clearly relevant to long-term industrial goals. Applications for intellectual property protection are handled by the Japan Science and Technology Corporation (JST).

SUPERCONDUCTIVITY RESEARCH

About thirty NRIM researchers work on superconductivity (only three on low temperature superconductors, Nb_3Al and multifilamentary V_3Si). Drs. Takeuchi and Inoue at Tsukuba Magnet Laboratories work on Nb_3Al. Collaborative work with industry (e.g., Hitachi and Showa) has been quite good, with results published openly and jointly in peer-reviewed scientific journals; however, some NRIM activities may be regarded by those with whom they do not collaborate (e.g., Fujikura) as being competitive. Collaboration with industry is handled typically on a "no-funds-exchanged" basis, with each party responsible for its own costs, and there is no mechanism for NRIM to receive funds from private sector companies.

Within NRIM's First Research Group headed by Dr. Togano, which is devoted to superconducting materials, there are four subgroups: (1) one headed by Dr. Kumakura looking at wires and tapes; (2) one headed by Dr. Hirata looking at more fundamental aspects such as the physics of mixed states using single crystals; (3) one headed by Dr. Nakamura looking at thin film physical growth mechanisms and device applications, and (4) one headed by Dr. Fukutomi looking at thin film processes for wires and tapes. This latter group is not using ion beam assisted deposition, but is developing novel cathodes for magnetron sputtering. Whereas nearly all work in superconductivity is done at Dr. Togano's First Research Group, there is also some materials and coil development being carried out at the High Magnetic Field Research Station. Because NRIM is a government institution, many of the more commercially oriented questions that WTEC panelists posed to NRIM were not relevant and hence were not answered.

Multicore Superconductivity Project

The overarching program objective today for superconductivity research at NRIM is derived from the second phase of the STA Multicore Project, which runs from 1995 to the year 2000. NRIM receives the largest share of Multicore Project funds, and all four groups mentioned above receive financial support from this project. Funding for the Multicore Project is fixed over a five-year period. Although program objectives are clearly defined, flexibility exists such that technical directions can be changed if necessary, and replanning is possible within and among groups and divisions. There is also the possibility of additional funding should a sufficiently provocative discovery warrant a request for an unbudgeted increment to pursue the new scientific or technical development. The two applications this project has targeted for development are an insert magnet for a 1 GHz NMR system and a magnetic separation unit that is being pursued in collaboration with MITI's Electrotechnical Laboratory (ETL). The WTEC team's hosts mentioned that the large-scale installation of NMR systems at Riken in Saitama is highly dependent on the success of the 1 GHz project. The magnetic separation project — the magnet will have a warm bore of about 15 cm and generate several tesla — has a practical goal of assisting in the cleaning of nearby Kasumigaura Lake. In spite of rapid advances in recent development of coated conductors with enhanced current-carrying performance, NRIM researchers feel that BSCCO-2223 is still the best candidate through the next five years for achieving the high performance target of 100,000 A/cm^2 in long lengths.

Superconductivity for Electric Power Applications

Since the technical focus of the Multicore Project is aimed at NMR spectroscopy and magnetic separation, only the more fundamental and performance-enhancing aspects of conductor-related research will be relevant to electric power applications. In these terms, the fiscal 1996 budget for HTS/LTS power applications was about ¥284 million, and the number of researchers was 13 (10 in HTS and 3 in LTS). The budget distribution for these two applications for 1995 and 1996 is as follows:

Year	NMR	Magnetic Separation
1995	¥170 million	¥72 million
1996	¥170 million	¥110 million

Funding for the balance of the project is expected to continue at this rate until completion of Phase II in 1999.

Conductor and Materials Development

Nearly 10% of NRIM's superconductivity budget (~¥100 million) and 70% of the staff in superconductivity (20 people) are applied to conductor and materials development. External organizations collaborate by sending researchers to NRIM and by winding coils. NRIM's role is to establish basic technology and make available its materials characterization facilities. Most scientists at NRIM are engaged in the study of BSCCO-2212, although there is some work being conducted on BSCCO-2223 and YBCO. Conductor geometries being studied include monocore, multifilamentary, and also coated tapes. The performance levels NRIM researchers have been able to achieve in these various systems are well documented in the scientific literature. Their major scientific and technical issues concern improving (1) uniformity and reproducibility of J_c along the tape length, (2) mechanical properties, and (3) high-temperature characteristics of the Bi-system. They see process optimization as the solution to item (1), since it is believed that inclusions randomly situated along the length of HTS tapes limit the uniformity of J_c. Silver alloys are also being used to address the mechanical properties issue; however, the price of a sharp improvement in strength of either the silver sheath or substrate is a degradation in J_c.

NRIM is doing no work on bulk materials or ac losses.

Power Generation, Storage, Transmission & Distribution

NRIM has no R&D programs in these areas.

End User Applications

About 10% of the superconductivity budget and manpower (¥110 million and three researchers) are applied to end user applications, mainly for magnetic separation in collaboration with ETL, which is doing the system development. NRIM's contribution to this program is magnet development. System designs and operating parameters have not yet been decided, but preliminary coil tests are being conducted. The major technical issue is the construction of a large-bore HTS magnet operating at higher temperature with either a cryocooler or liquid nitrogen. NRIM officials believe that there can be a market for high field magnets if HTS materials, which have higher upper critical fields than LTS conductors at low temperatures, can help produce high magnetic fields that lie outside the range achievable by LTS materials alone. The time to market is estimated to be anywhere from five to ten years. Depending on the frequency (resolution) required, LTS can handle systems up to 900 MHz, whereas systems greater than 1 GHz will require hybrids incorporating both LTS and HTS materials. No detailed comments were available for target costs or markets; however, the expectations for HTS products in the marketplace are as follows:

5 years	current leads
10 years	NMR, magnetic separation, cables, sensors

Site:	**New Energy and Industrial Technology Development Organization (NEDO)** **Energy Conversion & Storage Department** **3-1-1 Higashi Ikebukuro, Toshima-ku,** **Tokyo 170, Japan** **http://www.nedo.go.jp/index-e.html**
Date Visited:	3 June 1996
WTEC Attendees:	M. Suenaga (report author), R.D. Blaugher, J. Daley, G. Gamota, D. Gubser, D. Larbalestier, R. Schwall, R. Sokolowski, J. Willis
Hosts:	Shinichi Nakayama, Director General, Superconductivity Project Team Kimihiro Komatsu, Manager, Energy Conversion and Storage Department Kenichi Arai, Project leader, Applied Technology Development Department Masuharu Kazumori, Manager, Energy Conversion and Storage Department

BACKGROUND

The New Energy and Industrial Technology Development Organization (NEDO) was established in 1980, immediately after the second oil crisis, as a semigovernmental organization under the Ministry of International Trade and Industry (MITI) to promote technological development in Japan. NEDO is a unique organization in that it works to coordinate the funds, personnel, and technological strengths of both the public and private sectors. NEDO has an annual budget of nearly $2.5 billion (1995), $1.3 billion of which is expended for research and development of various technologies. As described below, NEDO has strongly supported applications of superconductivity for the electrical power utilities. Also, NEDO is a very strong supporter of the development of high temperature superconductors, as evidenced by its establishment of the International Superconductivity Technology Center (ISTEC). Of particular interest in this site visit was learning the details of NEDO's current programs, i.e., the areas of emphasis and the levels of funding, and especially of its future plans for superconductivity programs.

SUPERCONDUCTIVITY PROGRAMS

At the time of the WTEC team's visit, there were four programs on superconductivity at NEDO. Its two main programs are Superconductive Generator Equipment and Materials (Super-GM) and Superconducting Materials. The third, recently initiated, is Flywheel Energy Storage Systems. The fourth is on development of electronic applications of high T_c superconductors, which the team did not hear very much about, since this study focuses on power applications. Table NEDO.1 shows the budgets for these programs over a 10-year period, and Table NEDO.2 shows the manpower engaged in these programs in 1995.

Table NEDO.1
Budget for Superconductivity Projects, 1987-1996 (Unit: ¥100 Million)

Project*	**FY87**	**FY88**	**FY89**	**FY90**	**FY91**	**FY92**	**FY93**	**FY94**	**FY95**	**FY96**
Super-GM	---	14	17	23	29	34	36	36	39	26
FW Storage	---	---	---	---	---	---	---	---	3	5
SC Materials	---	5	9	13	18	20	35	23	22	23
Total	**---**	**19**	**26**	**36**	**47**	**54**	**71**	**59**	**64**	**54**

Table NEDO.2
Manpower for Superconductivity Projects

Project* / Year	NEDO	Entrusted	Companies
	FY95	**FY92**	**FY95**
Super-GM		273	232
FW Storage		---	90
SC Materials		110	108
Total	**5**	**383**	**430**

***Key to Projects**

Super-GM:	Superconducting Generation Equipment and Materials (Generator, Conductor, Refrigeration, System)
FW Storage:	High Temperature Superconducting Flywheel Energy Storage System
SC Materials:	Superconducting Materials

The Super-GM project includes development of low and high T_c conductors and refrigeration systems in addition to its primary objective, construction of a 70 MVA generator. The Superconducting Materials program supports the activities at ISTEC. The details of the generator development (Super-GM at Kansai Electric Power Co.) and of the development of superconducting materials (ISTEC) programs are described in the site reports of the respective locations and will not be discussed further here. The fourth and most recently established project (1995) is a feasibility study on a flywheel energy storage system. A part of this program's goal is to construct a 10 kWh flywheel using the melt textured RE-123 for the magnetic bearings. NEDO managers believe that for a flywheel energy storage system to be economical it should have a capacity on the order of 10 MWh. However, this project was not described in detail at the WTEC briefing. (MITI also supports a program to study a superconducting magnetic energy storage (SMES) system for load leveling of electric power. This is funded through Chubu Electric Power Co. and the details of the program are described in the site report for that company.)

The budget amounts listed in Table NEDO.1 are those disbursed by NEDO to cover the cost of a project; however, it is well known that the companies contracted to do the project will spend a significant amount of their own funds to support the project. Also, for relatively small projects such as the conductor development projects, the funds are distributed as an incentive to the participating companies in the program, and the companies may bear a substantial fraction of the total cost. Thus, total project funding could be significantly greater than shown in the table.

The aims of the high T_c conductor development part of the Super-GM program for the near future are depicted in Table NEDO.3. It is interesting to note that only a relatively small amount of funding is provided in the budget for development of the conductors utilizing high T_c superconductors, even though a very important development, e.g., $YBa_2Cu_3O_7$-coated conductor tapes at Fujikura, Ltd., has come out of this funding.

Perhaps the most interesting issues for the WTEC team are the plans for the next few years, as Super-GM and ISTEC are near the end of their first ten-year phase. There appears to be strong agreement that ISTEC will continue for another ten years, but it is possible that the nature of the activities at ISTEC's Superconducting Research Laboratory (SRL) and its associated laboratories may change significantly, e.g., give more emphasis to conductor development than is currently the case.

Table NEDO.3
Future Directions for Wire Development

1995	1996	1997	1998
Intermediate target: $J_C > 1 \times 10^4$ A/cm^2 $I_C \times L > 1{,}000$ A • m	→	→	Applicability to power apparatus
Long wire 300 m, 250 m (Bi)	Hundreds to →	1,000 meters →	Overall $J_C > 1 \times 10^4$ A/cm^2
Large I_C 4,100 A (Bi rods) 133 A (Bi stacked)	Increase in	I_C →	Large capacity current lead; conductor for power transmission cable
High J_C 1.1×10^6 A/cm^2 (Y) preliminaries (Tl)	Spray pyrolysis	increased length → increased length →	10 m long J_C wire, 1 T coil
Applications (trial products) 1 kA current lead	Increased I_C,	smaller heat leak →	Several kA current lead
Current limiter	Increase in current	capacity →	100 A

The future of Super-GM is less clear. There appear to be numerous possibilities for the next project. For example, Super-GM could be followed by another generator that is significantly larger in size (200-600 MVA) than the current unit (70 MVA). Another possibility is construction of a large (>1 GVA) power transmission cable utilizing high T_c superconductors. However, neither of these is likely to become reality for various budgetary and other reasons. Perhaps what may follow Super-GM will be a relatively small-scale conductor development program for a five-year period. To do this in a timely fashion, those involved in planning appear to be following a strategy of initiating a small program ($1-2 million) on conductor development starting as early as 1997 and bringing it up to a full-scale development program when Super-GM is completed. If this is to become reality, this project will likely emphasize ac applications and involve development of both low and high T_c ac conductors. At the time of this WTEC visit, it appeared that everything was in a very fluid state in regard to the next project in superconductivity, and it was not clear what would succeed Super-GM.

Besides these large projects in superconductivity, MITI in 1995 initiated a new program for NEDO to fund research at universities. In JFY 1995, the organization made 150 grants of approximately $1 million each, and it planned to continue at a level of 100 per year in the coming years. This is a totally new way of funding university research, which has been poorly supported in recent years. In the past, university researchers could only receive funds from the Ministry of Education, but starting in 1995, they can compete for funding from other sources such as this or from a similar program of the Science and Technology Agency (STA).

Site: **Railway Technical Research Institute (RTRI)**
Maglev System Development Department
Yamanashi Maglev Test Line
2-8-38 Hikari-cho, Kokubunji-shi
Tokyo 185, Japan
http://www.rtri.or.jp/

Date Visited: 23 June 1996

WTEC Attendees: D. Gubser (report author), D. Larbalestier, M. Suenaga

Hosts: Fuminao Okumura, Deputy General Manager, Planning Division, Maglev System Development Department, Railway Technical Research Institute
Shoichi Hashimoto, Director of Engineering, Chief of Construction Office, Railway Technical Research Institute, Yamanashi Test Line Construction Office

BACKGROUND

Japan's national superconducting Maglev (magnetic levitation) project aims to produce high speed (550 km/hr) commercial ground transportation in the 21st century. The Maglev project began in 1962 with testing of linear induction propulsion; in 1972 the first experimental superconducting Maglev test vehicle was operated; by 1979, a test vehicle attained a top speed of 517 km/hr at the Miyazaki Test Track; and in 1987 a two-car manned unit attained a speed of 400 km/hr on the same test track. Also in 1987, the Railway Technical Research Institute (RTRI) was formed as a research foundation and took over the research and development work for the Japanese Railway (JR) system. The Yamanashi Maglev test line, located in Yamanashi Prefecture, about 2-2.5 hours west of Tokyo by train or expressway, was approved for construction in 1989 with management by RTRI and JR.

The Yamanashi test line is the first section of a new high speed railway, the Chuo Shinkansen line, that is being constructed between Tokyo and Osaka, inland from the present coastal Shinkansen line. When completed, this section will be 42 km in length, 80% in tunnels, with a maximum incline of 4%. It will cost $3.4 billion. The initial construction is 18.4 km in length and was to be completed in 1997.

The 550 km/hr speed of the superconducting Maglev compares with the 350 km/hr of the fastest Japanese train today; 250 km/hr for the *Shinkansen* (bullet) trains; and 450 km/hr for the projected top speed of the German Maglev train. The German magnetic levitation work uses permanent magnets (not superconducting), and magnetic attraction forces (North to South poles) with active feedback control for stability, versus the magnetic repulsion (North to North poles) of the superconducting version, which produces intrinsically stable operation. The German version is in a more advanced state of development, but the Japanese superconducting version will attain a higher speed, will travel with a greater train/track separation (8-10 cm vs. 1-2 cm), and will be quieter in operation — all important features that keep the Japanese fully committed to the longer term development of their superconducting Maglev. Cryogenics is not an issue with the Japanese Maglev project.

PRINCIPLE OF OPERATION

At the heart of the Maglev system are the superconducting magnets used to levitate, guide, propel, and brake the train (Fig. Maglev.1). Levitation is caused by magnetic repulsion between the on-board superconducting coils (race track design, 5.3 tesla at the Nb-Ti coil windings) and the magnetic fields induced in nonsuperconducting track coils (figure-8 design) located on the sides of the U-shaped track. The figure-8 design provides stability to the train motion by balancing against both up and down motion. At equilibrium, the superconducting coils pass the figure-8 coils at the midpoint or crossover of the figure 8. No net circulating current is induced in the figure-8 coils in this case. If the train falls below the midpoint, induced currents are set up in the track coils, creating a repelling force from the bottom half of the figure-8 loop, and an attractive force from the top half of the loop (and verse versa if the train were to rise above the equilibrium point). Currents are induced in the track coils by the moving superconducting coils, and levitation begins after the train reaches a speed of 100 km/hr. For lower speeds, wheels are used. Guidance is provided by the same magnetic forces that repel the train from the track coils. Since the track coils are located on the sides of the track, induced currents from sideways motion repel the train if the train moves closer to that side. Propulsion is provided by linear induction where an ac magnetic field propagates down the track on a separate set of coils and pulls the superconducting magnets on the train if the phase is ahead of the train (acceleration) or retards the motion if the phase is behind the train (braking).

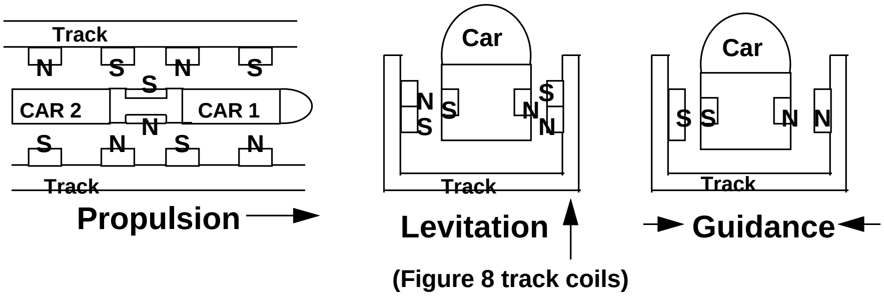


Fig. Maglev.1. Coil systems.

TRAIN SPECIFICATIONS

The cars on the Maglev have slightly smaller dimensions than the present high speed *Shinkansen* train in order to improve air resistance, and they are considerably (30%) lighter. To reduce the weight on the train as much as possible, the cars have aluminum alloy bodies, and even the seats are constructed of a lightweight composite structure. The outer skin will be shaped in a futuristic design to minimize aerodynamic drag and reduce noise — two front end designs are being tested. One design, manufactured by Mitsubishi Heavy Industries (MHI), has a “double cusp” feature that looks much like a duck’s bill; the other design, manufactured by Kawasaki Heavy Industries (KHI), has a wedge-shaped nose. A decision on which design is better will be made after test runs on the Yamanashi test line.

A three-car train (77.6 meters long, 2.9 meters wide, and 3.3 meters high) has been constructed by MHI, KHI, and Nippon Sharyo, Ltd., at a cost of $55 million. The cars carry almost the same number of passengers as the present *Shinkansen* train. The superconducting coils are located between cars so as to reduce passengers’ exposure to the magnetic field. Iron shielding will be used to further reduce the field to a level of about 20 gauss in the intercar passageway and much less in the passenger compartments. The train will “fly” with an 8 cm to 10 cm separation between the track and the body of the train.

The Maglev train will not have an on-board driver. Cameras located at the front of the train and fiberoptic cabling relay all information back to the control room, where operation is monitored and computer-controlled by a sophisticated traffic control system. Operators are currently conducting simulated train test runs in the control room to determine optimum operational parameters.

TESTING

The 18.5 km track will test/demonstrate several key aspects of the high speed Maglev transportation system:

- high speed runs at 500 km/hr with safety and comfort
- reliability and durability of vehicle and ground facility and equipment, including the SC magnets
- structural standards specifying a minimum radius of curvature and steepness of gradients
- distance between track axes, taking account of two trains passing each other (approach speeds of 1,000 km/hr)
- vehicle performance related to tunnel cross-section and the pressure fluctuations in the tunnel
- turnout performance
- environmental conservation
- multiple train traffic control system
- operation and safety system and maintenance standards
- control system between substations
- economy of construction and operation

Simulations of many of these tests were already underway at the time of the WTEC team's visit, affording training of control room operators. Actual testing was to begin in 1997.

ISSUES

The two largest issues for the Maglev project are (1) construction cost and (2) projected ridership. Costs of a Maglev line are about 50% greater than those of the high speed *Shinkansen* track. The largest cost item is the track rails. Advanced designs are being considered to reduce the number of coils and the amount of copper in the track coils. Similarly, alternative construction techniques are being used to minimize construction costs. The issue of ridership is simply a matter of trying to estimate the passenger traffic between Tokyo and Osaka in the future with both the *Shinkansen* line and the Maglev line being operative. The Maglev line will reduce the transit time from 2½ to 1½ hours, but the cost of a ticket will undoubtedly be more expensive.

ASSESSMENT

The Maglev project is a national project and is unique to Japan. Major construction of a commercial track is underway, and the project is funded for the next three years to complete the 42 km track. There appear to be no technical barriers to completing the Maglev project, although construction cost is still an issue. No one is predicting the future of the project after three years, but this author expects that if the economy improves, the project will continue to expand, and more track will be constructed. The completion date for opening the new high speed transportation line is far in the future, and the WTEC panel's hosts were unwilling to predict a completion date, even if all goes well. An estimate of 2030 to 2050 would perhaps be a realistic guess for beginning commercial operation of a superconducting Maglev train.

A fallback position should the Maglev prove to be too expensive is to convert the track to a conventional *Shinkansen* line. There is a definite commitment to a second high speed rail line, regardless of type, to provide alternative routes in case of major disruptions in one route. Thus, the new line will continue to be built. National pride and past development of the superconducting Maglev train make the future look promising for this application of superconducting technology. This project is a prime example of the Japanese long term vision and commitment to advanced technology.

Site: **Sumitomo Electric Industries, Ltd. (SEI)**
Osaka Research Laboratories
1-1-3 Shimaya, Konohana-ku
Osaka 554, Japan
http://www.sei.co.jp

Date Visited: 6 June 1996

WTEC Attendees: M. Suenaga (report author), D. Gubser, D. Larbalestier, J. Willis

Hosts: Ken-ichi Sato, Manager, Superconductivity R&D Department
Kazuhiko Hayashi, Chief Research Associate, Superconductivity R&D Department
Kazuya Ohmatsu, Senior Engineer, Superconductivity R&D Department

BACKGROUND

Sumitomo Electric Industries, Ltd. (SEI) is the world's second-largest producer of electrical cable, and this is its primary business. However, in recent years SEI has been diversifying its business into a number of other areas such as optical cables and specialty alloy products; currently, electrical cable sales are approximately one-half of SEI's entire business. The company is quite aggressive in R&D for new business opportunities and spends approximately 3% (~$250 million) of its sales per year on internal R&D. SEI has been working with superconductors since 1966, and it sells Nb-Ti wires for various applications. Following the discovery of high T_c superconductors, SEI researchers have aggressively pursued development of these materials for power as well as for thin film (electronic) applications (work on the films was not covered in this site visit). The SEI research team working on development of high T_c conductors is headed by Mr. Ken-ichi Sato; their contributions to the development of the Bi-2223/Ag tapes are well known throughout the world. SEI is one of the leading manufacturers of tapes, as well as of the magnets and cables that are made from the tapes.

SUPERCONDUCTING MATERIALS AND APPLICATIONS R&D

SEI's effort on superconducting materials and associated application development is carried out with ~35 researchers, of whom ~7 are devoted to development of thin film electronic applications. Another 7 work on the development of low temperature superconductors, such as Nb_3Al conductor for magnetic fusion (ITER) applications. SEI's Nb-Ti work is done in one of the business sections and is not included in the above total effort. The remaining 21 persons work on power applications of high T_c superconductors. The WTEC team was told that this effort is mainly supported by internal R&D funds, although some outside funds do come in support of these efforts, for example, from Tokyo Electric Power Company (TEPCO) for development of power transmission cables and YBCO-coated tapes; from Kansai Electric Power Company (KEPCO) for current leads and SMES coils; from Chubu Electric Power Company for terminations for superconducting power cables, and from Super-GM for development of Bi-2212 conductors. The following are highlights of SEI's accomplishments in conductor development, magnets, and large conductor applications.

Conductor Development

SEI researchers believe that the property of current Bi-2223/Ag conductors most in need of improvement is the critical current density for essentially all applications. They also believe that the key to improving J_c is in improving source powder uniformity, grain alignment, and thermomechanical processing; thus, they expend a strong effort in improving J_c in short and long tapes. Their current high values of the self-field J_c at 77 K are 42,500 A/cm^2 for short rolled tapes, 27,800 A/cm^2 for 114 m long tapes, and 17,700 A/cm^2 for 1,200 m tapes. They have also improved the mechanical properties of the composite tapes by additions of small amounts of Mn and Sb. In these ways they have been able to raise the critical tensile stress before the abrupt decrease in I_c from about 50 MPa to approximately 200 MPa. Another very interesting work being carried out without significant attention from the community is SEI's development of a $YBa_2Cu_3O_7$ coated conductor on Ni alloy tape. At present the best value of J_c at 77 K is 2×10^5 A/cm^2 for a 55 cm long and ~1 µm thick tape.

The significance of this work is the fact that this impressive number is achieved without use of the ion beam assisted deposition (IBAD) technique used by most other groups working on $YBa_2Cu_3O_7$ coated conductors. SEI is able to achieve a textured buffer layer on a metallic substrate by controlling the temperature and angle of the substrate with respect to the direction of the plume of yttrium-stabilized zirconia (YSZ) by laser ablation. By this technique, SEI researchers are able to obtain in-plane alignment of the YSZ buffer layer as good as 12.8° (FWHM). Although not as good as that achieved by the IBAD process (~7°), it is important to note that they can deposit the YSZ at a rate of 0.5 µm/min., compared with 0.025 µm/min. in the IBAD process. Another important and possibly limiting factor for this type of conductor is its relatively low overall J_c.

The WTEC team was told that another very important area requiring attention is reduction of ac losses at power frequencies in the Bi-2223/Ag conductors. Although the team's hosts did not describe the types of research that they are carrying out toward this objective, they gave the impression they are strongly interested in this subject and are likely be putting forward a significant effort to reduce ac losses in their conductors.

Cable and Magnet Development

SEI is a leading manufacturer of large-scale model magnets and power cables utilizing multifilamentary Bi-2223/Ag tape. Table SEI.1 lists SEI's accomplishments. One of its main efforts is in the construction of power transmission cables with TEPCO, and as shown in the table, researchers have successfully produced a 7 m 66 kV/1 kA three-phase cable that operates at 1 kA_{rms} load-in with an ac loss of 3.5 w/m cct. They have also produced a 50 m cable conductor with a dc I_c of 2,200 A. These cables have magnetic shielding to reduce ac losses in the metallic enclosure. Although the value of the ac loss that was measured for the 7 m cable is 5-10 times greater than the value desired for commercial cables, it is impressive that SEI is able to produce a production quantity of the tape with high critical currents. SEI researchers have also provided a more than 2 km length of the tape to Fuji Electric Co. for construction of a very interesting 500 kVA power transformer in collaboration with Kyushu University.

Table SEI.1
Development of Cables and Magnets

Application	Organization	Present Status	Features
Current Leads	KEPCO/Sumitomo	Implementation -SR Rings, SMES	2.5 kA, 0.4 W/kA 0.5 kA, 0.1 W/kA
Cable	TEPCO/Sumitomo	50 m Cable Model 50 m Cable Conductor (dc critical currents) 66kV/1kArms/3-phase	66 kV 2,900 A (10^{-12}W•m) 2,200 A (10^{-14}W•m) Magnetic Shield
Transformer	Kyushu Univ./Fuji	500 kVA	High efficiency
Magnet	Sumitomo	3 T at 20 K 0.66 T at 77 K	Stable
Magnet	MIT/Sumitomo	Btotal=24.0 T (4.2K) Btotal=23.4 T (27 K)	Double-pancake
Magnet	NRIM/Sumitomo	Btotal=21.8 T (4.2K)	Layer-wound

In the area of model magnets with Bi-2223/Ag tapes, SEI is also leading the pack for the highest field, which was generated by a Bi-2223 coil. Table SEI.1 shows some of the test results. Perhaps the most ambitious attempt in the construction of a coil is SEI's plan to make a 7-10 T magnet (by the end of 1996) that is entirely wound with Bi-2223 tapes and is to be operated with a cryocooler. This will certainly consume a large amount of high quality tape and will test SEI's tape fabrication expertise and facility. It is important to recognize here that SEI is gaining crucial experience in producing high quantity tapes at commercial scale while it is constructing these devices. Also, it is interesting to hear from the WTEC team's hosts that they do not see any substantial applications of the tapes sooner than 10 to 20 years from now, and yet they are making a very extensive investment in this area.

Site: **Super-GM Test Facility**
Engineering Research Association for Superconductive Generation Equipment and Materials (Super-GM)
Kansai Electric Power Company
Umeda UN Bldg. 2F
5-14-10 Nishi-Tenma, Kita-Ku
Osaka 530, Japan

Date Visited: 6 June 1996

WTEC Attendees: R.D. Blaugher (report author), J. Daley, G. Gamota, P.M. Grant, H. Morishita, R. Schwall, R. Sokolowski

Hosts: Takasuke Ageta, Managing Director
Makoto Kusuma, Senior Manager, System Department
Tatsumi Ichikawa, Senior Manager, Engineering Department
Hiroshi Kayama, Manager, Testing Center
Katsuyoshi Toyada
Noriyuki Yoshida
Akio Katagiri
Kouichi Ezaki
Koichi Inoue
Masamichi Chiba

BACKGROUND

In 1996 the Engineering Research Association for Superconductive Generation Equipment and Materials (Super-GM) entered the final installation, testing, and verification phase for the 70 MW-class superconducting generator model machine development. This program has been aimed at establishing technologies for the design and manufacture 200 MW-class pilot machines. This program, started in 1988, is administered by the New Energy and Industrial Technology Development Organization (NEDO) as part of the New Sunshine Program of AIST (Agency of Industrial Science and Technology) of MITI (Ministry of International Trade and Industry). The Super-GM program (Fig. Super-GM.1) involves 16 member organizations with representation from the electric utilities; manufacturers of electric power equipment; companies involved in both LTS and HTS research and manufacturing of wire and tape; refrigeration and cryogenic suppliers; and independent research institutes such as CRIEPI, which has assisted Super-GM with benefit and system analysis and electrical analysis for the stator and rotor.

Additional support on collaborative research and consulting is provided by universities and national research organizations such as the Electrotechnical Laboratory (ETL), which has provided basic research and technology assessment. NEDO provides direct funding to Super-GM in support of the generator design, construction, and test; conductor research on both LTS and HTS; the refrigeration system; and the total system integration and test. The 1996 budget of approximately $26 million was down from a peak in 1995 of $39 million. The manpower for the total effort averaged approximately 250 people/year from 1991-1996. MITI/AIST provided nearly $254 million in funding between 1988 and 1996. This figure has been complemented by additional support from member companies in what amounts to cost sharing of 20-50% of the contracted amount. The salaries for the technical staff assigned to the Super-GM organization in Osaka, for the most part, are directly paid by the individual companies (at approximately 250 people/year, the salaries alone would be $30-40 million). These staff members are rotated from the member companies on a two- to three-year basis, except for three persons, including Takasuke Ageta, the managing director.

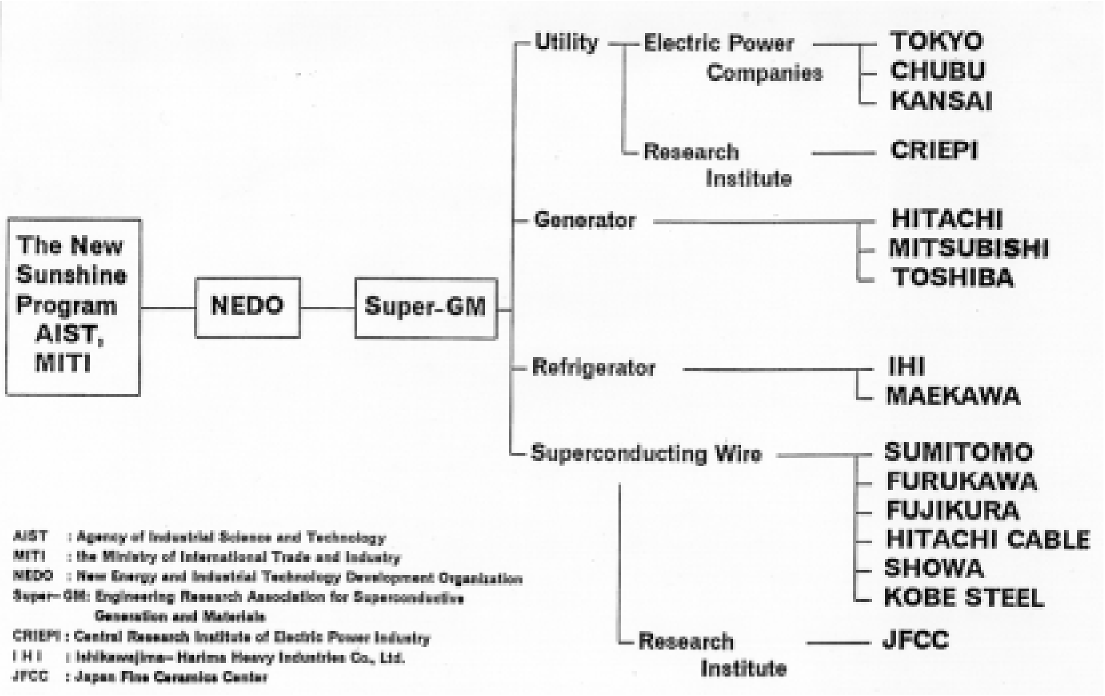


Fig. Super-GM.1. Organization of the Super-GM program.

VISIT TO THE SUPER-GM TEST FACILITY

Team B of the WTEC panel visited the Super-GM test facility under final construction at the Osaka Power Station of the Kansai Electric Power Company (KEPCO). The team was hosted by the managing director, Takasuke Ageta, and key members of the Super-GM organization involved in the construction and generator testing. Figure Super-GM.2 shows the test facility for the model machines, and Fig. 2.2 (page 16) shows its schematic layout. The construction work, started in June 1994, was nearly complete at the time of the WTEC team's visit. The first rotor (designated "slow-response excitation type A") and the "common" stator, both constructed by Hitachi, were delivered and installed in early 1997, with plans for five months of testing starting in June 1997. The schedule planned on testing all three rotors through 1998. Following the Hitachi rotor, the Mitsubishi rotor ("slow response B") and the final ("quick response") rotor from Toshiba will be installed and tested. The Nb-Ti conductor for these three rotors was supplied, respectively, by Hitachi Cable (slow-response A), Sumitomo (slow response B), and Furukawa (quick response). The schedule called for testing of all three rotors through 1998.

As shown schematically in Fig. 2.2, the Osaka verification test facility uses a back-to-back motor-generator (M-G) test method, with the addition of an induction motor that is used to bring the M-G up to synchronous speed. The helium refrigeration system constructed by Mayekawa is a 100 ℓ/hour closed cycle turbine-expander, screw compressor system. External LN_2 is used for additional precooling in the high temperature cold box heat exchanger. A preconditioning liquid He Dewar is used as a buffer to supply liquid to the generator. The first rotor and stator from Hitachi were factory tested at Hitachi prior to shipment to the test site. The second rotor from Mitsubishi likewise was also undergoing final testing at Mitsubishi's Kobe Works.

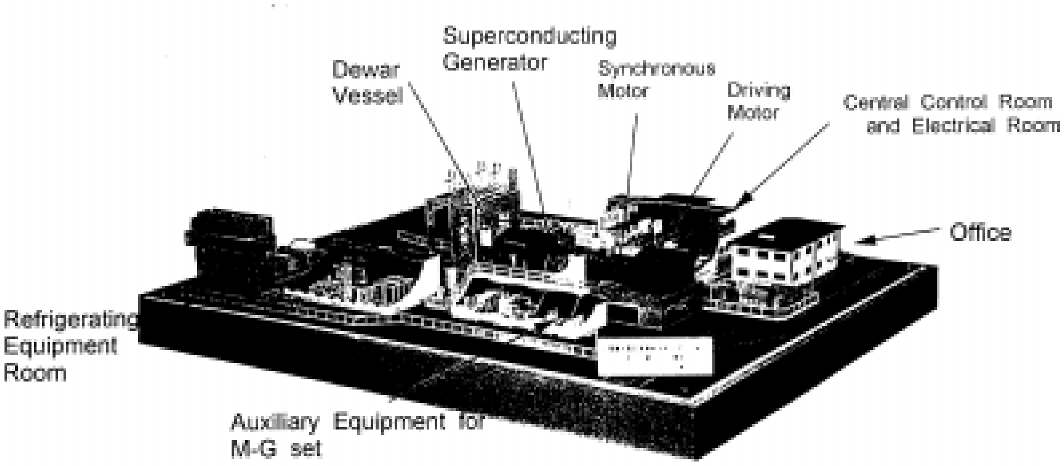


Fig. Super-GM.2. Schematic of the Super-GM test facility located at Osaka Power Station.

SC GENERATOR BENEFITS AND MARKET PROJECTIONS (PER SUPER-GM AND NEDO)

The 70 MW-class Super-GM effort is considered a “model” machine to establish technologies for design and manufacture of a 200 MW-class pilot generator. If the 70 MW class is successful, a future program targeted at 200-300 MW will be considered. The latter program would not provide 100% government support for manufacture. It is anticipated that the cost for a SC and a conventional machine would be nearly identical, at a 200-300 MW rating, using a 20-year lifetime. At present, the major advantage for SC generators is thought to be related to performance advantages for the power system, specifically with respect to steady state and transient stability, improved reactive power capability, and improved ability to tolerate negative sequence fields. It is also estimated that SC generators would lead to a ~30% increase in the power transfer limits for the transmission system. Additional benefits are the typical increase in efficiency of 0.5 - 1% and reduction in size and weight of ~50%. SC generators would also provide environmental advantages due to reduced oil consumption and reduction of CO_2 emissions. The forecast for sale of SC generators, with introduction expected by 2005, using only the national market for Japan, was estimated at $440 million/year for 20-30 units in the 200-600 MW range and ~2 units at 1 GW.

LTS AND HTS WIRE AND TAPE RESEARCH

The Super-GM research on superconducting wire and tape in support of power apparatus development has been conducted in parallel with the generator research since 1988 on both LTS and HTS conductors. The LTS effort has primarily focused on the development of low ac loss conductors for three different applications; an armature winding (Furukawa), a shunt reactor (Sumitomo), and a fault-current limiter (Hitachi). Three different types of Nb-Ti stranded wires with ~0.1 µm filaments and Cu-Ni matrix were developed by the identified manufacturers for the respective applications. The conductors showed reduced ac losses with acceptable current-carrying capacity of 2-3 kA.

APPROACHES FOR OBTAINING LOW AC LOSS

Approaches for obtaining low ac loss Nb_3Sn were also followed involving six different manufacturing processes: (1) the bronze process (Furukawa), (2) internal Sn (Sumitomo), (3) in-situ (Fujikura), (4) tube (Showa), (5) external diffusion (Hitachi Cable), and (6) powder metallurgy (Kobe Steel). The Nb_3Sn processed conductor, in general, was not as good as the Nb-Ti, having nearly one order of magnitude higher hysteresis loss than the Nb-Ti. The transport current was also lower than Nb-Ti at 1-2 kA. The normalized ac quench current at 50 Hz under a dc magnetic field of 0.5 T versus the cross-sectional area of the stranded wire (A_{rms}/mm^2) was roughly equivalent at 200-500 for both Nb-Ti and Nb_3Sn conductors. The Nb-Ti in general showed a lower ac loss than the Nb_3Sn at 50 Hz, ± 0.5 T. The Super-GM HTS research on oxide wire and tape development is oriented primarily at the future ability to apply HTS conductor to power apparatuses, including SC generators. The realization of an HTS conductor would simplify the cryogenic design. The basic design approach for an HTS rotor would be nearly identical to an LTS design.

The HTS wire effort, which also started in 1988, was at the time of the team's visit following 6 approaches:

1. Under long wire progress, Furukawa using a "multipipe" method for fabricating Bi-2223 has produced 300 m, $I_c = 4.4$ A, with a low Ag ratio of 1.3.
2. A Bi-2212 tape of 250 m was fabricated by rolling using Bi-2212 laser pedestal rods and silver matrix, a 100 m test length showed ~5A at 77 K.
3. Hitachi produced 100 m, thallium-free precursor on 50 µm Ag tape. Subsequent thallination produced a Tl-1223 thick film with I_c of ~5 A at 77 K for a 10-meter length.
4. The large current progress produced a Bi-2212 laser pedestal rod fabricated by Sumitomo with an I_c value of 4.1 kA at 77 K.
5. High current density progress was reported by Fujikura using laser deposition on a polycrystalline metal tape with a biaxial aligned YSZ buffer layer. J_c of ~1.1 x 10^6 A/cm^2 was observed at 77 K and just over 10^5 A/cm^2 at 5 T.
6. A long length of ~1 m also showed 10^5 A/cm^2 at 77 K.

Large area deposition progress for fault-current limiters reported two techniques: ionized cluster beam deposition (Toshiba) of Y-123 on $SrTiO_3$, which showed I_c of 60 A, and CVD (Mitsubishi) of Y-123.

Additional information on the Super-GM project can be obtained from several related publications presented at the ICEC 16/ICMC in Kitakyushu, Japan (May 20-24, 1996).

Site: **Tokai University, Shonan Campus**
1117 Kitakaname, Hiratsuka-shi
Kanagawa 259-12, Japan
http://www.u-tokai.ac.jp/English/index.html

Date Visited: 4 June 1996

WTEC Attendees: R. Sokolowski (report author), R.D. Blaugher, J. Daley, P.M. Grant, H. Morishita, R. Schwall

Hosts: Professor Kyoji Tachikawa, Faculty of Engineering, Department of Material Science and Technology
Professor Naoki Maki, Department of Electrical Engineering

BACKGROUND

The Tokai University Educational System (TUES) founded in 1942 by Dr. Shigeyoshi Matsumae has expanded into a comprehensive educational institution encompassing three universities — Tokai University, Kyushu Tokai University, and Hokkaido Tokai University — and a number of affiliated schools and research institutes in Japan and abroad, including junior colleges, secondary educational schools, an elementary school, and kindergartens. TUES has also established overseas hubs of activities: Tokai University European Center in Denmark, Tokai University Boarding School in Denmark, Tokai University Budo Center in Austria, and Tokai University in Honolulu, Hawaii. TUES has concluded academic exchange agreements with 16 foreign universities in 9 countries for the exchange of students and teaching and research personnel. Foreign students studying in TUES institutions number more than 400.

SUPERCONDUCTIVITY RESEARCH

Funding for research and development on superconductivity at Tokai University amounts to about ¥10 million per year (~$100,000 at $1 = ¥100), half of which comes from the university, which is privately funded, and the other half from the Ministry of Education and the Science and Technology Agency. Nearly 90% of funding is applied to conductor and materials development. External organizations collaborate with Tokai by providing use of their facilities and by fabricating conductors. Two professors and 21 students (1 doctoral candidate, 10 master's candidates, and 10 undergraduates) were working on superconductivity at the time of this WTEC visit.

The superconductivity research at Tokai University can be classified into three main categories:

1. Metallic superconductors, aimed at high field A15 superconductors and superconductors for ac use.
2. High T_c superconductors, involving the RE-123 oxides, Bi-2212 oxides, and Tl-1223 oxides. Professor Tachikawa's most significant contribution to achieving practical HTS conductors has been in the development of the diffusion process. The performance level(s) achieved in Bi-2212 is 30,000 A/cm^2 (4.2K, 10T) for a 0.15 cm^2 cross-section, and in Tl-1223 are 15,000 A/cm^2 (77 K, 0 T) and 1,500 A/cm^2 (77 K, 1.5 T) for a 0.075 cm^2 cross-section.
3. Versailles Project on Advanced Materials and Standards (VAMAS) international cooperation, consisting of six tasks:
   a) critical current measurement in Nb_3Sn multifilamentary wires
   b) ac loss measurement in Nb-Ti wires
   c) upper critical field measurement in Nb-Ti wires
   d) tensile measurement at 4.2 K in SUS 316 LN and YUS 170 steels
   e) fracture toughness measurement at 4.2 K in the same steels
   f) critical current measurement in high T_c oxide tapes.

Metallic Superconductors

The primary goal of the metallic superconductor program is to develop better A15 compounds for use in NMR applications. The most significant advance in processing techniques is the use of melt diffusion processing for preparing the intermediate compound Nb_6Sn_5, to which Ti and Ge can be added for enhanced performance and Cu can be added to reduce the optimum heat treatment temperature. Fig. Tokai.1 is a flowchart of the sample processing sequence. Nb_3Sn processed in this way exhibits improved properties over Nb_3Sn processed by the bronze route. Normal state resistivity is increased threefold (Fig. Tokai.2), and the potential of 21 tesla operation is clearly evident (Fig. Tokai.3).

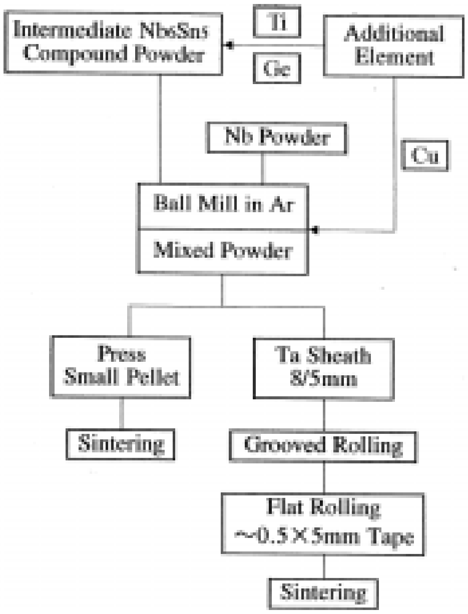


Fig. Tokai.1. Flowchart of a sample processing sequence.

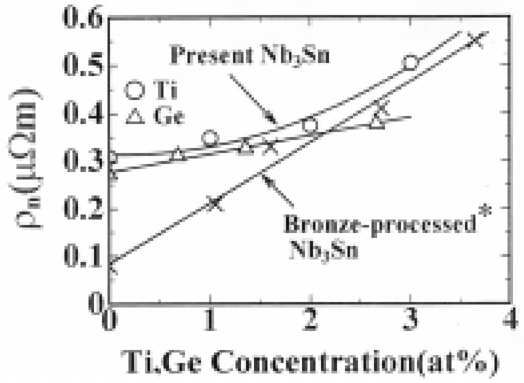


Fig. Tokai.2. Normal state resistivity increased threefold (H. Sekine, K. Itoh and K. Tachikawa, *J. Appl. Phys*., 63 [1988]:2167).

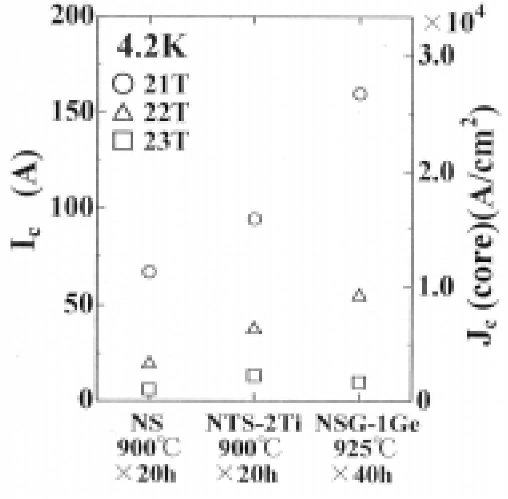
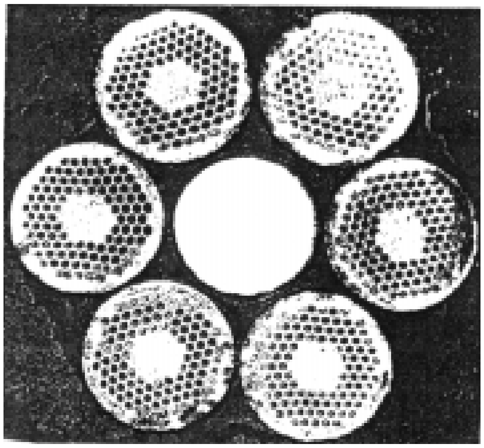


Fig. Tokai.3. Potential of 21 tesla operation.

Superconductivity for Electric Power Applications

The Nb-Ti cable developed for ac use consists of 6 elemental Nb-Ti wires around a central SUS 316 LN steel wire. Figure Tokai.4 shows the characteristics of the elemental wire and cable dimensions. The small filament diameter and the alloyed Cu matrix (Cu-2.5 without Si) contribute to favorable performance in ac application. The Si in the matrix also diffuses to the filament/matrix interface, creating a thin Si layer that provides a barrier against adverse interdiffusion, which would result in impaired performance of the superconducting filaments. Tests of this cable's ac properties were made on a 100 kVA test coil (winding ID/OD of 45 mm/111.5 mm, and height of 70.3 mm) that was wound and assembled at Furukawa and tested at CRIEPI.

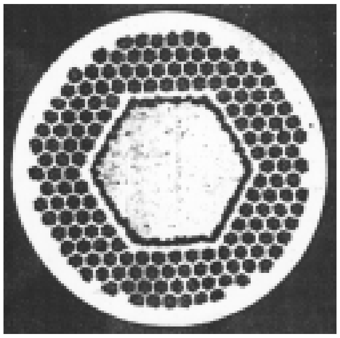


Elemental Wire

Wire Diam.:	0.203 mm	Cable:	Six elem. wires
Matrix:	Cu-2.5wt% Si	Central Wire:	SUS 316 LN
Filament:	Nb-50wt% Ti	Cable OD:	0.75 mm
Filament diam.:	0.14 µm	Cable Length:	467 m
No. of filaments:	164,730		
Cu ratio:	1.08		
Twist pitch:	1.9 mm		

Fig. Tokai.4. Characteristics of the elemental wire and cable dimensions.

Central Cu/bronze-processed Nb_3Sn wire also has submicron filament diameter, over 17,000 filaments, and an overall diameter less than 0.3 mm (Fig. Tokai.5). The addition of Ta to Nb filaments prevents their ribbon-like deformation, reduces the proximity effect, and enhances the critical current density (Fig. Tokai.6). Additional alloying of small amounts of Ge increases J_c even further and contributes to significant reductions in hysteresis loss. Wire incorporating these improvements that was made at Hitachi cable for the Super-GM project exhibits substantially smaller hysteresis losses when compared to non-alloyed Nb/Cu-5Sn (Fig. Tokai.7).



Outer diam.	0.284 mm
Fil. Diam.	0.70 μm
No. of fil.	109 x 162 = 17,658

Fig. Tokai.5. Central Cu/bronze-processed Nb_3Sn wire.

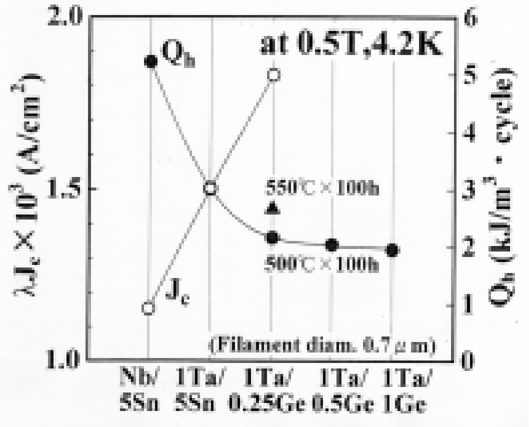
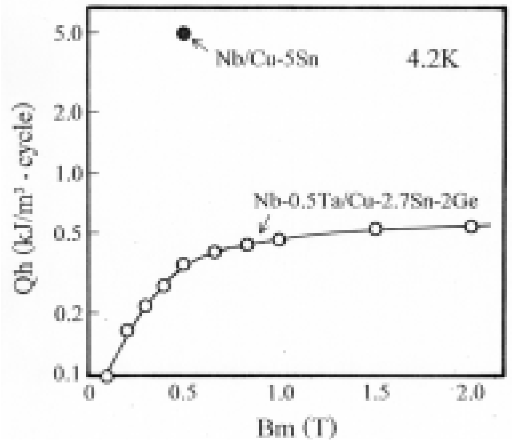


Fig. Tokai.6. Reductions in hysteresis loss.



Core/Bronze	Nb/Cu-5Sn	Nb-0.5Ta/Cu2.7Sn-2Ge
Local Bronze /Core Ratio	2.05	4.7
Filam. Diam.	0.70 μm	0.20 μm
No. of Filam.	17,658	75,990
Wire Diam.	0.284 mm	0.284 mm
Twist Pitch	2.3 mm	2.3 mm

Fig. Tokai.7. Hitachi cable for the Super-GM project exhibits substantially smaller hysteresis losses compared to non-alloyed Nb/Cu-5Sn.

High T_c Oxide Superconductors

With demonstrated success in melt diffusion processing of Nb-Sn compounds, Professor Tachikawa's group has applied diffusion processing to oxide superconductors. By applying a lower melting point layer onto a substrate having a higher melting point, an HTS layer can be formed with the attributes of shorter reaction time, greater thickness, and improved homogeneity. This technique has been applied successfully to RE-123 compounds, Bi-2212, and Tl-1223.

Figure Tokai.8 shows the required layer stoichiometries needed to form these compounds. Fig. Tokai.9 gives actual data representing the compositional variation across the various interfaces for the case of Nd-123, where the product layer is around 150 microns. Fig. Tokai.10 is a schematic of a phase diagram and the development of the reaction layer by diffusion. Processing Gd-123, which has a smaller ionic radius than Nd, results in a 300 micron 123-layer under identical processing conditions.

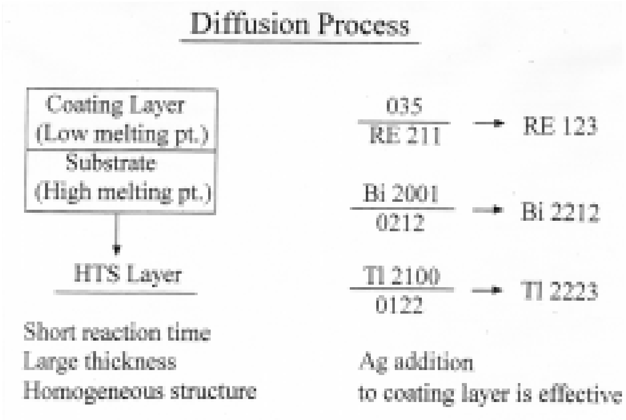


Fig. Tokai.8. Required layer stoichiometries needed to form RE-123, Bi-2212 and Tl-1223 compounds.

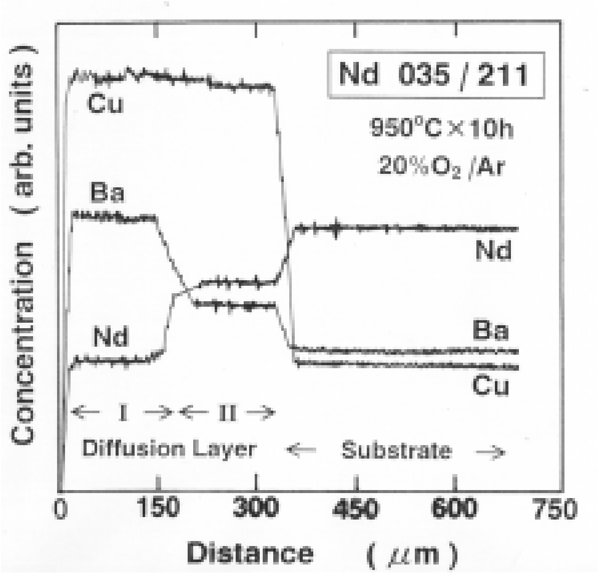


Fig. Tokai.9. Actual data representing the compositional variation across the various interfaces for the case of Nd-123.

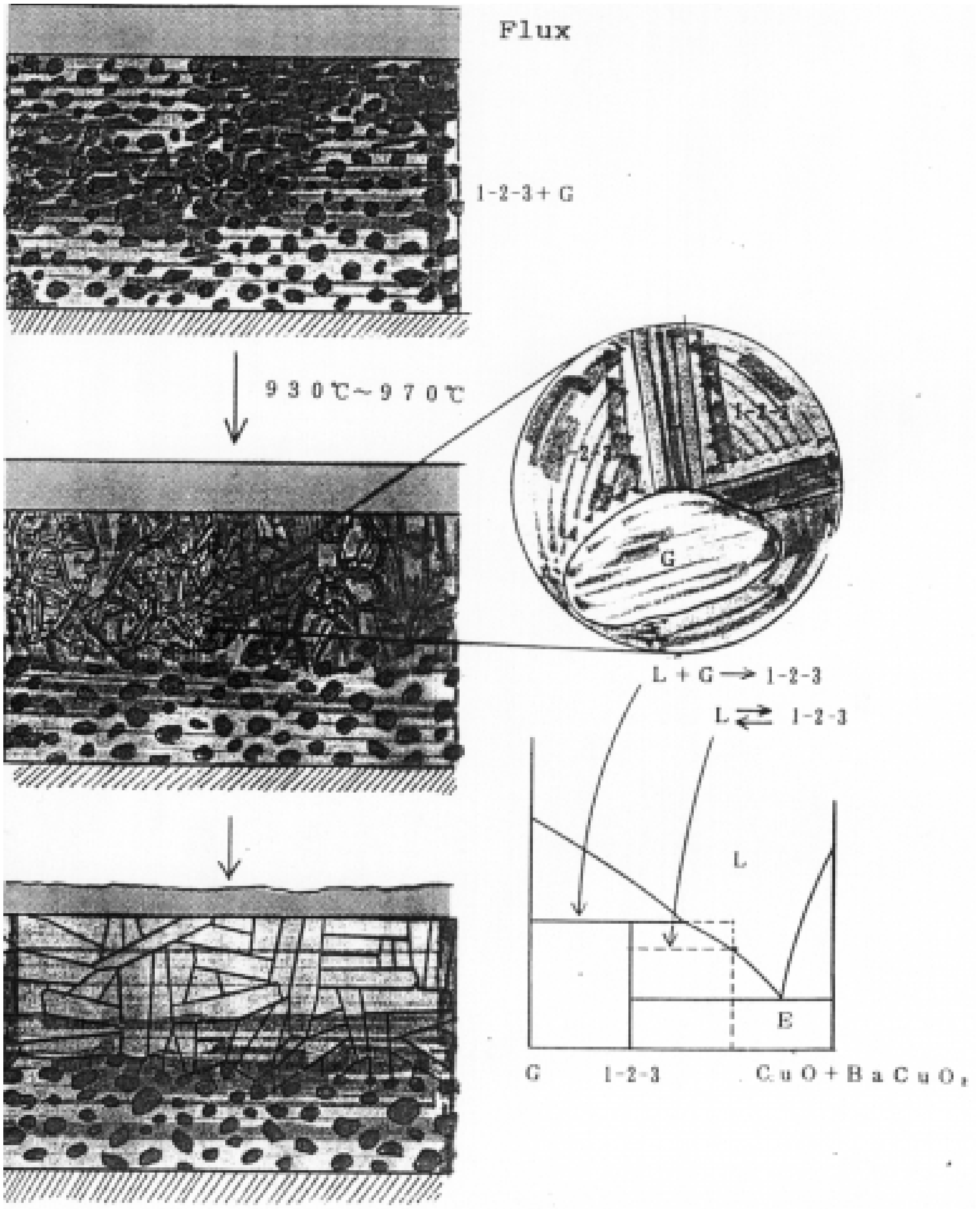


Fig. Tokai.10. Schematic of a phase diagram and the development of the reaction layer by diffusion.

Tl-based high T_c oxides are also easily synthesized by diffusion reaction (Fig. Tokai.11) in a short reaction time. TlF substituted for Tl_2O_3 produces a dense structure and acts as an effective flux to transform the 2223 phase into the 1223 phase. Without this fluorine addition, 1223 is hardly formed, even after very long reaction times. Fluorine is lost in the reaction. In F-substituted specimens, the c-axis lattice parameter of the 1223 phase formed reaches a slightly smaller value than that reported (Fig. Tokai.12), and transport I_c at 77 K is also vastly improved (Fig. Tokai.13), even more so when the sample is cooled slowly after reaction (Fig. Tokai.14). Annealing in flowing O_2 at 600°C after reaction decreases normal state resistivity and improves transport I_c at 77K. J_c of about 15,000 A/cm^2 has been obtained in thick layers through F addition and post-annealing in O_2.

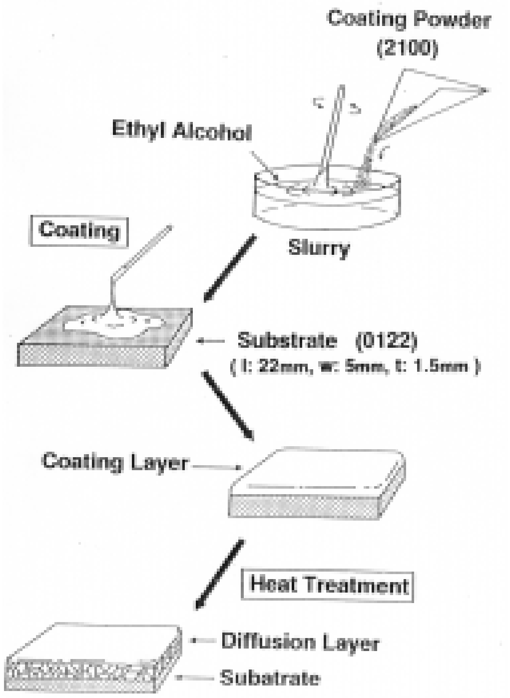


Fig. Tokai.11. Tl-based T_c oxides synthesized by diffusion reaction.

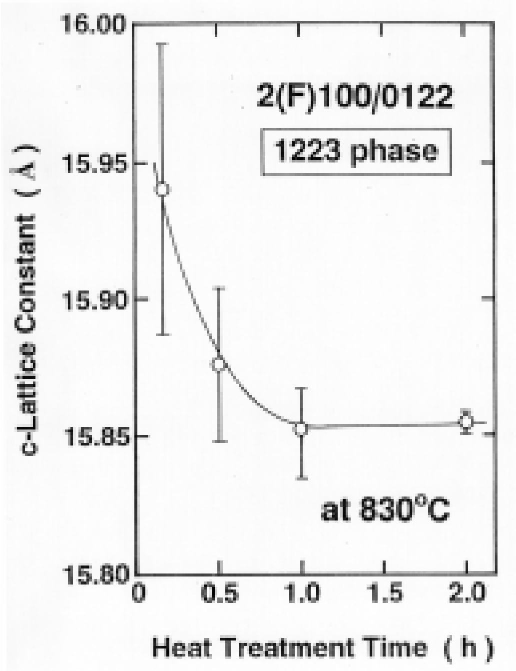


Fig. Tokai.12. F-substituted specimens with c-axis lattice parameter of the 1223 phase.

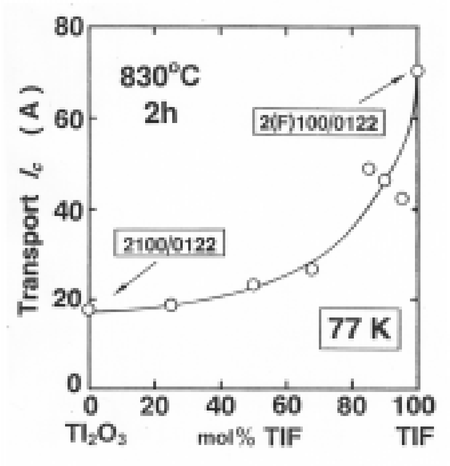


Fig. Tokai.13. Transport I_c at 77 K.

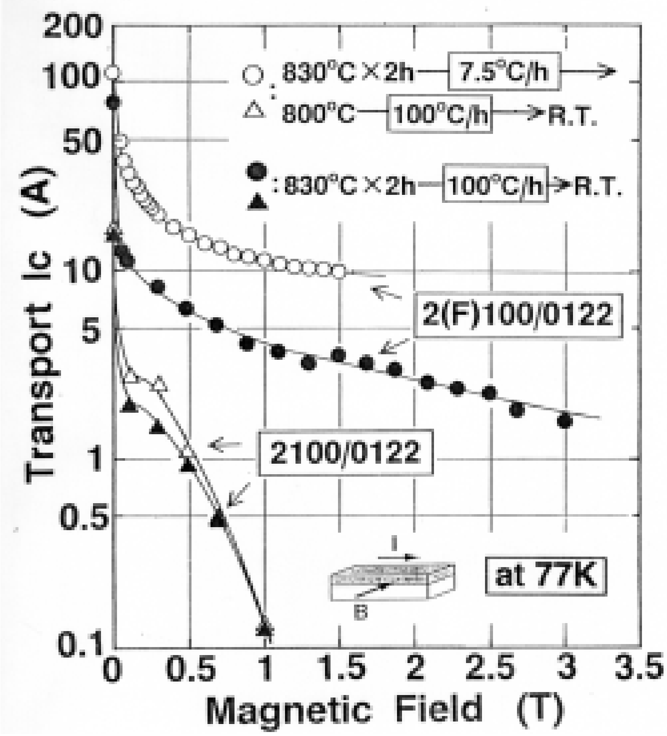


Fig. Tokai.14. Improved Transport I_c at 77 K when cooled slowly after reaction.

Power Generation, Storage, Transmission & Distribution

Other than the conductor-related research mentioned above which includes ac loss reduction in metallic superconductors and enhanced operating temperature and J_c enhancement in Tl-compounds there are no specific R&D applications programs in these areas of electric power technology. At this time there are no plans to conduct any research on improving the ac loss characteristics of high temperature superconductors.

Other Applications

Two application-specific research activities at Tokai University have involved using the diffusion techniques outlined above to produce HTS current leads and magnetic shielding tubes. The current leads are made of Bi-2212 and can be operated from 4.2 K to 30 K. The I_c for 3 mm diameter rods at 30 K and 0.5 T are 200 A, and the associated heat leak through 50 mm long rods of this diameter were measured to be 19 mW, which is acceptable for the available refrigeration power at 4.2 K. See Fig. Tokai.15 for the current-field characteristics of Bi-2212 produced by the diffusion process. The magnetic shielding tubes were made from Y-123. Data on the flux exclusion performance are available in *Adv. Cryogenic Engineering* 140(1994): 253-260.

No detailed information was available for target costs or markets; however, the expectations for HTS products in the marketplace are as follows:

5 years	tapes and small magnets, bulk magnets, film-based devices
10 years	fault-current limiters
20 years	motors, generators, transmission lines, MRI, levitated trains, etc.

The principal opportunities for new magnets are for high field magnets and cryocooler refrigerated magnets with HTS displacing LTS/HTS hybrids ten years later.

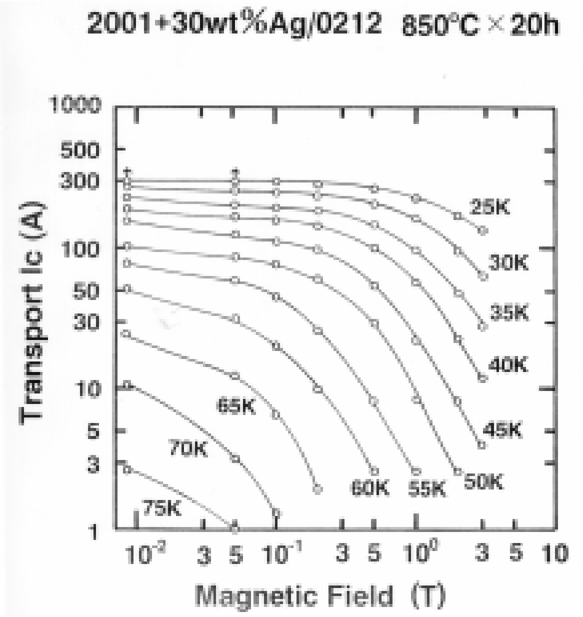


Fig. Tokai.15. Current-field characteristics of Bi-2212 produced by the diffusion process.

Site: **Tokyo Electric Power Company (TEPCO)**
Power Engineering R&D Center
Insulation and Power Apparatus Department
4-1 Egasaki-cho Turumi-ku
Yokohama 230, Japan
http://www.rd.tepco.co.jp/

Date Visited: 4 June 1996

WTEC Attendees: R. Schwall (report author), R.D. Blaugher, J. Daley, G. Gamota, H. Morishita, R. Sokolowski

Hosts: Dr. Hara Tsukushi, Group Manager, Insulation and Power Apparatus Department
Hideo Ishii, Senior Engineer, Insulation and Power Apparatus Department

BACKGROUND

TEPCO is the largest utility in Japan, providing roughly one-third of the country's power. Its service area is centered around Tokyo and covers roughly 10% of the area of Japan. Peak demand is 69 GW, and generation is from a mixture of hydroelectric, fossil fuel, and nuclear plants.

Tables TEPCO.1 and TEPCO.2 and Fig. TEPCO.1 show TEPCO's Power Engineering R&D Center staffing, budget, and general history; areas of activity; and organization. Staff effort in superconductivity (SC) is approximately 10 people: 5 in the lab and 5 outside. Yearly R&D expenditures are about $1 million on power lines, $1 million on fault-current limiters, and $0.5 million on Super-GM support.

Table TEPCO.1
Power Engineering R&D Center Statistics

Fiscal Year	1970	1975	1980	1985	1990	1993	1994
Number of staff members	91	101	117	128	135	145	134
Research budgets (¥ hundred million)	45.7	32.0	26.3	49.2	71.8	92.7	102.0
Number of research themes (number of projects)	54	65	67	100	80	98	149
Number of patents applied for	14	43	35	53	115	88	72
Number of patents granted	5	34	10	5	26	32	-
Number of presentations at academic society mtgs.	-	-	-	53	209	275	188

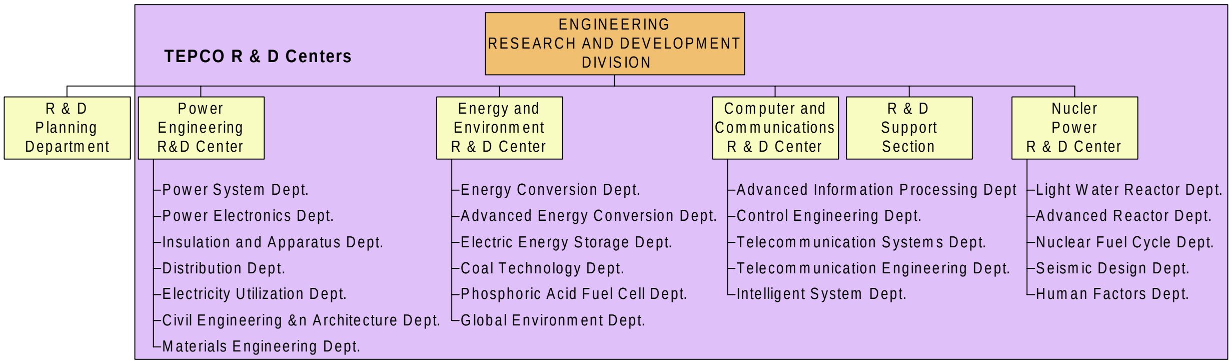


Fig. TEPCO.1. Organization of TEPCO R&D Center.

Table TEPCO.2
History of TEPCO Power Engineering R&D Center

August 1959	The Engineering Research Center was established.
October 1960	The Center was placed under the jurisdiction of the newly established Technology Dept.
May 1966	The Center was placed directly under the jurisdiction of the President: the Research Management Dept. and the Power System Dept. were newly created.
June 1968	The newly organized Research and Development Planning Dept. was set up: the Research and Development Administration System was adopted.
October 1968	The Engineering Research Center moved from Kameido to Tsutsujigaoka.
June 1970	The Research and Development Administration reorganized as the Research and Development Center.
June 1979	The Development Dept. and the Technology Research Dept. were added.
September 1983	The Civil Engineering Dept. was renamed as the Civil Engineering and Architecture Dept.
June 1985	The Research and Development Center reorganized as the Research and Development. Administration and the Engineering Research Center, Engineering Development Center, Nuclear Power Research and Development Center were established
June 1987	The R&D Planning Dept. and the Computer and Communication Research Center were newly instituted, and the Computer and Communication Research Dept. of the Engineering Research Center was renamed as the Power System Dept.
October 1994	Inauguration of TEPCO R&D Centers (generic name) with reorganization of Engineering R&D Div. Reorganization of Engineering Research Center into Power Engineering R&D Center. Transfer of Materials Engineering Department for Nuclear Power R&D Center to Power Engineering R&D Center. Establishment of Power Electronics Department, Insulation and Apparatus Department and Electricity Utilization Department by reorganizing related departments.

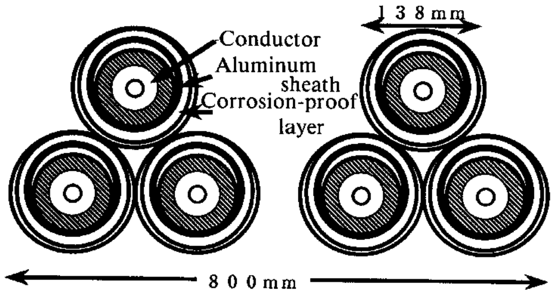
SUPERCONDUCTIVITY PROGRAM

TEPCO is active in three SC areas: power transmission lines, fault-current limiters, and the Super-GM generator.

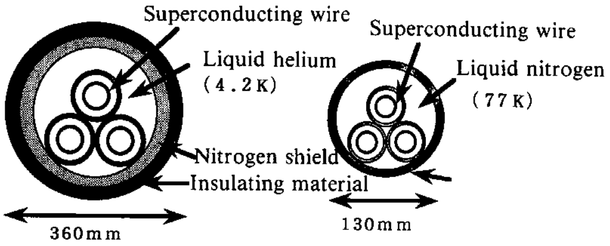
Superconducting Power Transmission Lines (SPTL)

Requirements

A much larger fraction of TEPCO's transmission and distribution (T&D) lines are underground than for a comparable U.S. utility. This is due to the fact that transmission from hydroelectric plants must be accomplished via tunnels through mountainous terrain, as well as to the need to bury lines in TEPCO's largely urban service area. Lines up to 275 kV are oil-filled, and those at higher voltages (up to 500 kV) are dry (cross-linked polyurethane, XLPE). Capacity is from 250 to 1,000 MVA/circuit using cable ducts up to 150 mm ID. The objective of the superconducting cable program is to provide additional capacity in the existing ducts, thus avoiding the cost and disruption of excavating to install additional ductwork. Figure TEPCO.2 provides a size comparison of HTS, LTS, and conventional cables for 1,000 MVA transmission. TEPCO analysis indicates that the design providing 1,000 MVA in a 130 mm dia. duct will require a current density in the superconductor of 10^5 A/cm^2.



(a) OF cable (275 kV, 1,000 A, double circuits)



(b) Metallic superconducting cable (66 kV, 9,000 A, single circuit) (c) High-temperature superconducting cable (66 kV, 9,000 A, single circuit)

Fig. TEPCO.2. Comparison of relative sizes of 1,000 MVA cables using various technologies.

Project Overview and Funding

TEPCO has a cooperative SPTL program with Sumitomo Electric and Furukawa, which began with Furukawa in 1987. Funding is $2 million/year and is flat; $1 million of that is provided by TEPCO and $500 thousand each by Sumitomo and Furukawa. This level of funding appears to support the fabrication and test of SPTL prototypes and not the underlying work to improve the performance of the superconductor.

Demonstration Cables

Tables TEPCO.3 and TEPCO.4 give specifications for 4 demonstration cables, designated as A, B, C, and D.

Table TEPCO.3
Specification and Testing of the High T_c Superconducting Cable Prototypes

	Prototype-A	**Prototype-B**
Specifications	3-phase, 66 kV/1 kA$_{rms}$ (114 MVA)	Single-phase, 66 kV/1.4 kA$_{rms}$ (38 MVA)
Length, OD	7 m, 130 mm ∅	5 mm, 124 mm ∅
Others	Magnetic shield layer	66 kV-class terminations
Testing	3-phase continuous current flow (1 kA$_{rms}$, 7 hours)	Load test (66 kV/1.4 kA$_{rms}$, 15 min.)

Table TEPCO.4
Specification of 50-Meter-Long Conductors

		Conductor-C	**Conductor-D**
Wire	width x thickness J_c at 77 K & self-field	0.185 mm x 3.3 mm 10,000 A/cm^2	0.28 mm x 4.1 mm 18,000 A/cm^2
Conductor	Length, OD I_c at 77 K ac transmission	50 mm, 38 mm ∅ 1,700 A 2,000 A$_{rms}$	50 m, 23 mm ∅ 2,900 A 2,200 A$_{rms}$

Technical Challenges

The primary technical challenges are seen as critical current density and ac loss. TEPCO researchers have doubts about the ability of BSCCO to provide the required 10^5 A/cm^2 current density. Their feeling is that acceptable ac loss can be achieved if the cable strands are transposed to force current sharing.

Fault-Current Limiters (FCL)

System Requirements and Current Program

TEPCO researchers see a need primarily for transmission-level fault-current limiters because they continue to add generating capacity to the TEPCO grid, thus increasing the available fault current at existing breakers. At the time of the WTEC team's visit, the maximum system voltage was 500 kV, and the maximum circuit breaker interrupt capacity has recently increased from 50 kA to 63 kA. Development of a 80 kA breaker was underway, but TEPCO management wanted to limit fault current to <63 kA.

In about 1989, TEPCO started a program with Toshiba Electric to develop an LTS parallel inductor limiter. The primary application is transmission at 500 kV, but the 1996 prototype was rated at 2 kA$_{rms}$ and 6.6 kV. The choice of a parallel inductor design was driven by the desire for a limiter that does not require a trigger signal. In addition, a large premium is placed on compactness, given the limited space in Japanese substations. Work to date has concentrated on reducing the refrigeration requirement for the FCL, and this is now at 3.4 W/phase, which is described as "almost acceptable." The limiter goes normal in about 150 ms, and the voltage transient associated with the quench is such that metal oxide varistors (MOVs) will be used to suppress it in the high voltage design. The TEPCO system employs transmission breakers that open in 100 ms and reclose after one second. Distribution breakers open in 100 ms and reclose after one minute. A distribution limiter must, however, survive 6 to 10 reclosures. Recovery time of the 1,000 A 6.6 kV prototype coil was two seconds.

Future Plans

The TEPCO strategy for controlling fault currents is to install solid state breakers initially, then migrate to FCL as the technology matures. The acceptable cost for an FCL in the intertie position is the cost of ten breakers, and that in the feeder position is "much lower." A very limited number of applications is seen for distribution-level current limiters. The transmission-level FCLs are seen as HTS because they can be conduction-cooled in a helium-free system using an 8 W refrigerator that was developed for the Maglev program. The voltage breakdown of helium in a transmission system is seen as a serious problem. The TEPCO program plan calls for development of a 3-phase distribution-level limiter in three to four years and a field test in this century. The transmission level limiter is predicted to be available in 2010.

Super-GM

TEPCO has assigned three persons to Super-GM. TEPCO management anticipates that the generator will be the first power application of superconductivity to be tested, but the FCL will be the first to be installed in the grid. TEPCO interest in superconducting generators is likely to be confined to units of 1,000 MW and higher.

SMES and Flywheels

TEPCO management sees SMES of interest only if it is applied to diurnal load leveling at power levels of several GW. They do not see an application for smaller SMES, and the WTEC team's hosts commented that power system stabilization controls are less costly than micro-SMES and work well. Even at 10% of its current cost, they would regard micro-SMES as expensive. They are actively following the Nippon Steel/ISTEC flywheel project but have no internal effort.

Site:
Toshiba Corporation
Toshiba Heavy Apparatus Laboratory (Keihin Operation)
2-4 Suehiro-cho, Tsurumi-ku
Yokohama, Japan
http://www.toshiba.co.jp/index.htm

Date Visited: 5 June 1996

WTEC Attendees: M. Suenaga (report author), D. Gubser, D. Larbalestier, J. Willis

Hosts:
Dr. Masami Urata, Deputy Manager, Superconducting Technology Group, New Energy Technology Department
Mr. Susumu Mine, Chief Specialist, Advanced Research Devices Staff, Machine and Equipment Department
Dr. Yutaka Yamada, Senior Research Scientist, Research Laboratory, Energy and Mechanical Research Laboratories, Toshiba Research and Development Center
Mr. Yoshihiro Waichi, Group Manager, Electromagnetic Engineering Department, Superconducting Magnet Group

BACKGROUND

Toshiba Corporation is one of Japan's largest manufacturing companies. Its business covers a wide range of products, from home appliances and semiconductors to large electric power equipment. The WTEC team visited Toshiba Heavy Apparatus Laboratory (Keihin Operation) in Yokohama, where Toshiba manufactures its large electric equipment (electrical generators, large motors, etc.). All of its large superconducting apparatus is also constructed at this site, after extensive R&D of the particular system is performed at the Toshiba Research and Development Center at another site. Toshiba has been interested in applications of superconductivity for many years and has manufactured a number of high field magnets and other superconducting systems. Some currently active applications were discussed at the site visit, and these as well as Toshiba's outlook on applications of high T_c superconductors are summarized briefly below.

SUPERCONDUCTING APPARATUS PROGRAMS

At Keihin Operation, there are four main projects, all currently at the manufacturing stage:

1. superconducting rotor for Super-GM
2. large coil for a SMES project managed by ISTEC for NEDO (MITI)
3. superconducting fault-current limiter for Tokyo Electric Power Co.
4. cryogen-free high field superconducting magnet.

All of these magnets employ low T_c superconducting components, except for the current leads for the fault-current limiter and the cryogen-free magnet. Toshiba also manufactures magnets for magnetically levitated trains, but these are constructed at its Fuchu Works, where the primary business is transportation products. The Keihin Operation also produces large magnets for single crystal growth of semiconductors and for MRI. Before discussing the technical aspects of these main activities, it is important to note that the WTEC team came away with the strong impression that as a result of the construction of many types of devices over the years, the Keihin Operation of Toshiba maintains a tremendous knowledge and expertise in the manufacturing technology of superconducting and cryogenic devices. Most of these construction activities probably are supported by one type or another of national or power company project, even though Toshiba also puts in a substantial amount of its own R&D funds.

Superconducting Rotor for an Electric Power Generator

As a part of the Super-GM project, Toshiba has been actively engaged in research and development of the superconducting generator. (See the Super-GM site report about the scope of this project.) Toshiba's part of the project is to study a quick-response-type rotor, and it has constructed a half-length rotor to be tested in-house. The objective of this study is to design, construct, and verify the design of a superconducting rotor that can respond quickly enough to external electrical disturbances to provide electrical system stability. In constructing this rotor, Toshiba had to develop a new type of Nb-Ti wire with Furukawa Electric Cables, Ltd., in order to minimize ac losses due to a sudden large change of magnetic field (3.8 T/sec). It has conducted in-house a number of tests to verify the suitability of the rotor for the quick-response-type generator. At the time of the WTEC visit, it was constructing a full-sized model rotor for the 70 MVA generator, to be tested in 1998 at Super-GM's Kansai site. During the tour of the factory, the WTEC team was shown at a distance the half-length unit, and it was quite an impressive sight.

Superconducting Magnetic Energy Storage (SMES) Coil

This is a part of MITI's SMES program managed by ISTEC, and the WTEC team did not find out many details about this project. However, as an initial step in studying a 100 kWh 20 MVA SMES pilot plant, Toshiba has constructed a large coil (~3.5 m in OD and 0.23 m in thickness), which is being tested at JAERI and was to be sent in 1997 to Lawrence Livermore National Laboratory in the United States for further tests. This R&D coil has the same diameter but only one-half the thickness of the unit required for the pilot plant. The complete system requires 12 full-size units. One interesting feature of the coil is its use of cable-in-conduit Ni-Ti conductors for very high currents (20 kA). The cable contains Nb-Ti wires designed for low ac loss that incorporate CuNi matrix and oxidized strand surfaces to reduce interstrand coupling. The panel's hosts did not discuss the program beyond the testing of the coil.

Superconducting Fault-Current Limiter

This is a project that is carried out in collaboration with Tokyo Electric Power Co. that has been going on since about 1990. At the time of the WTEC team's visit, Toshiba had recently constructed a 6.6 MVA (6,600 V/1,000 A) single-phase unit. The unique feature of this unit was that it was a closed system, i.e., it did not require replenishment of liquid helium because it incorporated a 4.2 K refrigerator in the unit. It also employed high-stability and low-ac-loss Nb-Ti wire as well as high T_c superconducting current leads, which helped to reduce the size of the unit. The next stage of the current limiter project, as the team was told, is to focus on improvement of the insulation so that the voltage can be raised to the 500 kV level. Toshiba engineers are planning to accomplish this by 2010.

Cryogen-Free High Field Superconducting Magnets

One of the very popular activities in the area of superconducting applications in Japan is construction of cryocooled high magnetic field magnets. With widespread availability of high T_c superconducting current leads, it has become possible to construct superconducting magnets that will run without the use of liquid helium. Because liquid helium is very expensive in Japan, the idea of having a superconducting magnet that can be turned on without the need for liquid helium has became very attractive, and a number of manufacturers have produced these magnets for sale. Toshiba is one of the first to commercialize a couple of models, a 5 T magnet with a 300 mm warm bore and a 10 T magnet with a 100 mm warm bore. The 10 T unit is particularly impressive. To achieve this, Toshiba incorporates a special 4 K cryocooler that was developed at the Toshiba Research and Development Center and is now being manufactured by a subsidiary.

HIGH T_C MATERIALS DEVELOPMENT PROGRAM

The high T_c materials program at Toshiba is carried out at the Toshiba Research and Development Center with approximately ten staff members. This effort is primarily focused on fabrication of Bi-2223/Ag tapes and current leads and is lead by Dr. Y. Yamada. One of his recognized accomplishments is the fabrication of Bi-2223/Ag tapes with the highest reported critical current density achieved at the time of 6.6 x 10^4 A/cm^2. In the process of making the high J_c tapes, he has pointed out the importance of the green powder density in the tape throughout the mechanical deformation process in order to achieve high current density tapes. More recently, his group has successfully incorporated Mg in the Ag matrix to improve the tape's mechanical strength to 120 MPa. It also fabricates the current leads for incorporation into Toshiba's devices such as the current limiter and the cryogen-free magnets when these are being studied. However, it was not clear to the panel whether or not Toshiba's commercial units contain Toshiba's own current leads.

It appears that the Toshiba R&D Center staff are interested in the investigation of high T_c materials only to the extent that they have knowledge of the processes and the limits of each material, for possible future product applications. They believe that knowledge of the conductors may be important for construction of some devices in the future. Toshiba's relatively small interest in this subject is due to the fact that the company is not a prime manufacturer of wires and cables. In the past, its researchers have also studied and developed low T_c wires as R&D projects, and some of the results from the studies were incorporated in production of the wires by Showa Electric Cables, Ltd., with which Toshiba works quite closely from time to time. A similar scenario is also possible with high T_c materials, as Showa is fabricating both Bi-2212 and Bi-2223/Ag tapes.

Site: **University of Tokyo**
Department of Superconductivity
Hongo, 7-3-1 Bunkyoku
Tokyo 113, Japan
http://www.appchem.t.u-tokyo.ac.jp/labs/kitazawa/superconductivity/index/html

Date Visited: 7 June 1996

WTEC Attendees: D. Larbalestier (report author), D. Gubser, M. Suenaga, J. Willis

Hosts: Prof. Koichi Kitazawa, Department of Applied Chemistry and Department of Superconductivity

BACKGROUND

Professor Kitazawa's group has played a vital role in the development of HTS right from the beginning of HTS studies in 1986. It was the first group to identify the 214 phase responsible for superconductivity in Bednorz and Mueller's mixed-phase samples, presenting its seminal results at the crucial Materials Research Society Meeting in December 1986 at which the discovery first became widely known. Several professors at Tokyo University collaborated to make important early strides and became influential in setting the stage for much of the early scientific work in HTS in Japan. As the field has matured, the effort at Tokyo University has continued to strengthen and to remain influential; important efforts by Prof. Kitazawa, Prof. Kishio, and Prof. Yamafuji (now retired) have kept the effort in the forefront worldwide. There is now a Department of Superconductivity at Tokyo University, and Prof. Kitazawa is Professor in both this department and the Department of Applied Chemistry. He is the senior person in the field at Tokyo University and enjoys high regard in the field throughout the world. The WTEC team visited him on the last day of its trip to Japan, hoping to synthesize various impressions from our trip. We received a number of important insights from our discussions there.

SUPERCONDUCTIVITY IN JAPAN

Our conversation covered the past and the future. An overall theme was that there is a strong belief in Japan that superconductivity will be a vital technology of the 21st century. This belief motivates the Japanese approach to the subject, which is perhaps more patient than the U.S. view. Japanese scientists and companies have been very active in superconductivity for more than 25 years, and the discoveries of HTS, in which Japan played an important role, have only served to confirm their interest. For example the Super-GM program (see also the site report on this national project) was approved at least in part because of the HTS discoveries. The combination of LTS device development (generator) and HTS materials development looks perhaps disconnected in the short term but very logical in the context of a 21st century approach to the technology.

RECENT CHANGES IN THE FUNDING OF RESEARCH IN JAPANESE UNIVERSITIES

There have been many recent changes to the Japanese budget process and to the way that universities are funded. Among the important new trends is that the government has explicitly determined to fund science and technology (S&T), rather than just large projects involving S&T, because in the past large projects often have had the bulk of their money spent on land acquisition and construction. As part of the government economy priming to help Japan recover from the recent recession, MITI and STA have explicitly targeted money to universities. Prof. Kitazawa had been on a panel that had evaluated about 2,000 applications for these awards by MITI/NEDO. About 100 awards of about 1 million dollars each were made, seven of which were in the general area of superconductivity. This scheme was at first only for one year, but a second-year award in fiscal year 1996 of about $50 million brought the total amount given out to $150 million.

STA also introduced a similar scheme, improved, however, in that the money and time scale were increased to a total of $100 million available for selected projects each year for five years. Prof. Kitazawa won one of these awards and used it to help Dr. Tonomura of Hitachi Research Laboratory complete the funding of a 1 MeV electron holography microscope. This project needed about $30 million for total funding; Prof. Kitazawa's $10 million represented the external match required by Hitachi. This project is a highly successful continuation of an existing program that was funded by ERATO.

GENERAL COMMENTS ABOUT THE FUNDING OF UNIVERSITY RESEARCH

Professors Kitazawa and Kishio have very well equipped labs with relatively stable teams of about 15 graduate students each. To run such labs, they estimated that they required about $300 thousand per year; in contrast to U.S. or European labs, they do not pay their graduate students, and this money is therefore solely for operating expenses. It is provided by a combination of grants from the Ministry of Education (Monbusho) and industry. The Monbusho university budget for all scientific research comes to about $1 billion per year. There are about 150,000 researchers in Japanese universities, who together make about 70,000 applications a year, of which about 20,000 are successful. The typical grant is about $50 thousand per year.

Additional new funding for universities is coming from JSPS (Japan Society for the Promotion of Science) in the amount of $100 million, the money being distributed to about 500 professors. The goal of this new program is to raise the level of funding for some outstanding groups, bringing their funding level closer to that of leading U.S. and European groups.

Like the U.S. industry, Japanese industry is often not very concerned about university research, but a program of the JST (Japan Science & Technology Corporation, funded by the STA[2]) can fund industry to exploit patents that are obtained by Japanese universities. For example, Sumitomo Electric Company benefited in the amount of about $10 million from STA on the basis of patents filed by Tokyo University and NRIM on HTS materials. In spite of this, the motivation for the work at Tokyo University remains focused on scientific discovery. This theme appears to motivate a lot of the work in Japan. It appears that the large MITI program in HTS will continue for another ten years because HTS is still seen to be precompetitive, in spite of its very large application potential.

MISCELLANEOUS TRENDS

In a wide ranging closure to the WTEC team's discussions with Prof. Kitazawa, a variety of themes emerged. One aspect of Prof. Kitazawa's approach to HTS is to broaden the potential applications of superconductivity. He showed the team a horizontal bore (warm bore 5 cm) refrigerated "dry" magnet made by Toshiba. This had been operating in his labs for over a year and was so convenient that students much preferred using it over transferring liquid helium into more capable "wet" magnets. A separate fund of $10 million was being used to purchase magnets for several other research institutions. The general goal of this aspect of Prof. Kitazawa's work was to study the influence of strong magnetic fields on common phenomena, for example corrosion. Some of the magnets would be sent to other university groups with interests outside superconductivity, but the largest component of this venture involved making magnets for a foundry institute in Saitama Prefecture, where there was an interest in new technology, and one of the possible areas of study involved fluidity control using strong fields.[3]

---

[2] Formerly known as Japan Research and Development Corporation (JRDC). JRDC and the Japan Information Center for Science and Technology (JICST) were combined into JST in October 1996.

[3] See *WTEC Panel Report on Advanced Casting Technologies in Japan and Europe* (1997) for further details on Japanese R&D in use of magnetics in the foundry industry. Full bibliographic information is listed on the inside back cover of this report. Also available on world wide web: http://itri.loyola.edu/casting/b_nagoya.htm.

Site:	**ABB Corporate Research** **Baden-Daetwil** **Switzerland**	**U.S. Contact:**	**ABB-TTI** **1021 Main Campus Drive** **Raleigh, NC 27607**

Date Visited: 13 June 1996

WTEC Attendees: R.D. Blaugher (report author), D. Larbalestier

Hosts:
Ove Albertsson, Manager, Department of Power Engineering, Vasteras, Sweden
Willi Paul, Head of Applied Physics Group, Baden-Daetwil
Harry Zueger, Research and Development Engineer, Transformers, ABB Secheron, Ltd.
Jacob Rhyner, Computer Engineering Department, Baden-Daetwil

BACKGROUND

The ABB Group was formed in 1988, primarily from the merger of Asea (Sweden) and Brown-Boveri (Switzerland). ABB now operates a number of “independent” business units throughout the world, principally in Switzerland, Sweden, Germany, and the United States, engaged in the research, development, and manufacture of a wide range of electric-power-related components (e.g., switchgear, transformers, generators, overhead and underground transmission cables, and power conditioning for motors and transmission system stability). As a result of the promising business outlook for superconducting electric power components, the ABB group has supported R&D on superconductivity for many years in both LTS and HTS. Past research primarily focused on energy storage (SMES), SC generators, transformers, and fault-current limiters. Even though ABB is a major supplier of both overhead and underground transmission cables, it has not pursued SC transmission. ABB previously studied both dc and ac SC transmission and concluded that their economics combined with their refrigeration requirements made them unattractive.

ABB is following SC cable development and would consider future efforts in this area, dependent on progress in its current programs. Energy storage, strongly followed by ABB in the past, is considered an important area. At the time of the WTEC team’s visit, ABB had been developing a major SMES system for the Swiss railroad, but this was terminated due to the realization of an alternate, less costly, solution. ABB has no current plans for storage but will continue to evaluate the technology. The support for superconductivity technology within ABB is fairly strong and represents support from upper management from both the research side and the business units. ABB will continue to support R&D on SC technology to provide “core” capability within the research and business units in the event that commercialization of SC power devices is demonstrated to be feasible. In that regard, the WTEC team’s hosts at ABB indicated that the company’s eventual commercialization of HTS power devices will be completely dependent on the realization of a satisfactory HTS conductor with acceptable performance and cost.

CURRENT HTS RESEARCH AND DEVELOPMENT

ABB’s major research effort at the time of the team’s visit was focused on development of HTS transformers and fault-current limiters, with essentially equivalent interest devoted to these two activities. ABB had considered SC transformers for some time and earlier had constructed an LTS prototype for evaluation and for developing practical experience. This early effort encouraged pursuit of the program directed at eventual development of a mid-range 100 MVA (220 kV/15 kV) transformer using HTS windings and operating at 77 K with liquid nitrogen. ABB researchers feel that realization of HTS transformers at 100 MVA, which is typical for Switzerland, would show a significant reduction in weight (approximately 50%) and electrical losses (approximately 70%) and offer a marked capital cost advantage of nearly 20% over conventional transformers. The ABB approach assumes realization of an HTS conductor with $J_e = 10^4$ A/cm^2 at 0.1-0.2 T and specific ac losses of 0.25 mW/Am. ABB is currently working on a joint project to demonstrate a 630 kVA, three-phase transformer with HTS windings. This joint effort involves ABB Baden-Daetwil, the ABB Secheron transformer facility located in Geneva, Switzerland, Electricité de France, SIG (the electrical utility for Geneva, Switzerland), the Swiss Federal Office of Energy (BEW), the Swiss Electric Association (VSE, PSEL), other Swiss utilities (CREE), and also American Superconductor Corp. (U.S.), which is supplying the HTS conductor. Table ABB.1 presents the design specifications for the 630 kVA transformer.

Table ABB.1
HTS Transformer Specifications

Rated power	630 kVA, 3 phases
Rated voltages	18.72/0.42 kV
Rated currents	11.2/866 A
Frequency	50 Hz
Impedance	4.6%
Coupling	Delta-Wye

The other major program underway at ABB-Daetwil is directed at use of HTS materials for demonstration of a fault-current limiter. The ABB interest in superconducting fault-current limiters (SCFCL) is driven by the high mechanical and thermal stresses imposed on the switchgear and transformers due to short-circuit (I_{sc}) transient conditions on interconnected electrical systems. The objective is to reduce these stresses, proportional to I_{sc}^2, to a level where the fault current doesn't exceed 10 times the normal current. The SCFCL should have these primary features:

- negligible influence on the electrical system under normal conditions
- instantaneous limitation of all types of faults
- ability for repetitive faults, i.e., short recovery time
- no over voltages
- self-triggering
- high reliability with fail-safe capability

ABB has built and tested several prototypes of an SCFCL based on a design referred to as the "shielded iron core concept." The ABB device consists of a warm iron core, which under normal operation is shielded by a superconducting cylinder enclosed in a fiberglass liquid-nitrogen-cooled Dewar. A normal conducting (Cu) coil, connected in series with the line, is wound external to the Dewar/SC cylinder. Under normal operation the SC cylinder isolates, i.e., "shields," the copper coil from the inner Fe, resulting in a low impedance, similar to an air-core reactor. Under fault conditions, the field induced in the copper coil is sufficient to "normalize" the SC cylinder, allowing flux penetration, thus linking the Fe core to the copper coil with a resultant increase in impedance and an immediate lowering of the fault current. ABB constructed and tested a 100 kW prototype using a stack of four Bi-2212 rings, 8 cm long, 20 cm diameter, wall thickness d = 1.8 mm, that were individually melt-processed in a rotating Ag mold. The total height of the stack was 35 cm. Tests were conducted at 480 V with fault-currents of 8 kA at different phase angles of the source voltage. For the two extreme phase angle conditions at peak source voltage and at zero source voltage, the fault current was limited to a peak value of ~900 A or ~5x the normal current. ABB researchers feel the shielded core device can be scaled to MVA values, which would allow test and possible installation in electric systems with high faults and low operating currents, e.g., in the excitation, auxiliary, and startup branches of power stations. A new ABB three-phase 1.2 MW FCL is now in operation in a power station in Löntsch, Switzerland.

Site: **Forschungszentrum Karlsruhe GmbH (FZK)**
Institut für Technische Physik (ITP)
P.O. Box 3640
D-76021 Karlsruhe, Germany
http://www.fzk.de

Date Visited: 14 June 1996

WTEC Attendees: R.D. Blaugher (report author), D. Larbalestier

Hosts: Prof. Dr. Peter Komarek, Director, Institute for Technical Physics, FZK
Prof. Dr. H. Rietschel, Director, Institute for Nuclear Solid State Physics, FZK

BACKGROUND AND CURRENT HTS RESEARCH AND DEVELOPMENT

The Karlsruhe Research Center (Forschungszentrum Karlsruhe, FZK), which was formerly known as the Karlsruhe Nuclear Research Center, KfK, is one of the largest government laboratories in Germany. The primary research activities at FZK currently cover four main areas: environment, energy, microsystems engineering, and fundamental research. The employment level at FZK is nearly 3,000, which includes approximately 1,200 scientists and engineers and typically an additional ~100 guest scientists and ~200 predoctoral students. The research division of FZK has sixteen scientific institutes with a total annual budget of DM 520 million, of which approximately DM 400 million is specifically labeled for research and development. Around DM 80 million of the total budget is derived from external contract research.

The superconductivity effort at FZK falls mainly under two of these institutes: the Institute for Technical Physics (ITP), Prof. Dr. Peter Komarek, Director, and the Institute for Nuclear Solid State Physics (INFP), Prof. Dr. H. Rietschel, Director. Additional contributions come from the three divisions of the Material Research Institute (IMF I-III), whose directors are Prof. Zum Gahr, Prof. Munz, and Prof. Hausselt, respectively.

Most of the “high current” applied superconductivity R&D at FZK is concentrated in the Institute for Technical Physics, with just one project in Rietschel’s group on flywheels and processing of melt-textured YBCO. Fusion research, which had been one of the primary activities under the previous KfK charter, continues to be the main focus for the ITP. The German fusion project is part of a major European effort that involves all states of the European Union, except Greece and including Switzerland. The primary fusion-related effort for the ITP is in the area of SC magnets using conventional liquid-helium-cooled conductors. The budget for SC magnet R&D is ~25-30% of the total fusion budget. The rest of the superconductivity research within the ITP is directed at basic superconductor material development with emphasis on HTS, and at engineering applications of SCs, which includes high field magnets and all power engineering.

Excluding the fusion effort, the superconductivity R&D for the ITP is spread over these specific projects:

- physics of SC, mainly on HTS (together with INFP)
- thin films, including applications (together with INFP)
- development of HTS bulk materials and conductors — Bi-2223 tape and melt-processing of YBCO
- high field magnets — Homer I & II and NMR
- cryogenic development — pulse tube refrigeration and thermal insulation for transmission lines
- power engineering — SMES; transmission cable work with Siemens; high voltage terminations for cables; fault-current limiters, which includes a collaboration with the Israelis on an inductive design; and all International Energy Association activities
- structural materials (together with IMF II)

The overall budget for all of the superconductivity programs at FZK, excluding fusion, is ~DM 30 million and involves 90 man years. Table FZK.1 presents the manpower and budget for power engineering and fusion activities accorded to the identified research areas.

Table FZK.1.
Superconductivity Programs at FZK

Research Areas	Man Years	Budget (DM M)
HTS (including all power applications)	16	4.6
LTS	7.5	2.15
High Field Magnets	7	3.1
Fusion	60	15.25

The funding for this effort is mostly internal and comes from German government sources, ~90% from the Federal Republic of Germany and ~10% from the State of Baden-Wurttemberg. Part of the fusion budget (~20-25%) comes from Euratom, and some of the HTS support (~10-15%) comes from Brussels (the European Union) under the BRITE-EURAM and ESPRIT programs. The majority of the staff salaries (~90%) are paid from the government funding. The overall funding for SC has been fairly stable and is expected to continue to be stable over the next few years.

SPECIFIC POWER-RELATED AND HTS PROGRAMS

FZK has a major SMES program, which also involves five German utilities. This program addresses a power quality problem related to “flicker” due to the frequent startup of large motors at a saw mill. FZK is presently constructing a 250 kJ SMES with a toroidal field design to minimize the stray field. Its analysis indicates that a SMES system is ideal for reducing the flicker, due to the SMES fast response capability. The SMES program is benefiting from some of the past research on fusion, which has produced acceptable approaches for the high voltage (HV) terminations and rapid field changes in SC coils. These HV terminations can also be used for the SC cable program. FZK is also studying the use of SMES as a pulse power source for providing ~10 GW pulses with a 2.0 ms duration at a 10 Hz rate to power rf klystrons at the Deutsches Electronen Synchrotron (DESY) laboratory.

The flywheel program, discussed earlier, is directed by the INFP using melt-processed YBCO for the bearings. INFP has advertised and offered for commercial sale semifinished cubes, cylinders, and rods of melt-processed YBCO. A 300 Wh flywheel model has been built and tested by INFP using superconducting bearings combined with permanent magnets. The flywheel system, using disks constructed from advanced carbon fibers, was operated from 30,000 to 50,000 rpm and produced 10 kVA/300 Wh at 50,000 rpm. The electric drive system for the flywheel was developed in cooperation with the Institut für Elektrische Maschinen und Antriebe of Stuttgart University. The next step in the program is to develop a larger flywheel, with a capacity of ~ 7 kWh/250 kVA, together with industry and accompanied by application studies with the utilities. The overall storage program at FZK, which includes the flywheel activity, is currently budgeted at ~ DM 1.4 million and involves ~ 6 man years of effort (these manpower and budgetary estimates are included in Table FZK.1). For the next steps, if approved, additional external funds will be added.

The HTS conductor program at ITP within FZK is fairly significant and is currently budgeted at ~DM 2.8 million with a 10-man-year level of effort (these figures also are included in Table FZK.1). The primary activity is directed at Bi-2223 development with plans in the near future, together with the INFP, to look at a textured substrate approach similar to the ORNL “RaBiTs.” FZK’s conductor program, which collaborates heavily with industry, has provided several hundred meters of Bi-2223 conductor to Siemens for the cable program. FZK is looking at alternative sheath materials for improved strength and reduced ac losses by twisting and by use of a mixed matrix. Also of interest is a push to reduce the overall cost of the Ag sheathed powder-in-tube conductor approach.

GENERAL MARKET AND PROGRAM PROJECTIONS

Prof. Dr. Komarek expects the next major application effort at FZK to be on fault-current limiters, which are of interest to German utilities in the 110-380 kV range for reducing faults on transmission interties. There is currently no major interest within these utilities for development of SC generators, motors, transformers, or SC transmission lines, even though research is being carried out on this last technology. Serious market interest in cables and transformers as defined by potential orders from the utilities may be as much as 20 years off.

Komarek expects the market for HTS inserts for high-field magnets (> 20 T) to develop within the next five years. Magnetic separation is also an area that may expand, especially with the integration of a “cryogen-free” design. The European market is viewed as cautious for all HTS products, with only the HTS leads enjoying a near-term opportunity; in fact, the leads are viewed as a present commercial reality.

Komarek indicated that the overall market projections for superconductivity presented at the 1996 International Superconductivity Industry Summit (ISIS) were highly optimistic. The German estimates as expressed through the Consortium of European Companies (CONECTUS) study were more conservative and probably more realistic. He provided the data for projected SC markets that are shown in Table FZK.2, which only applies to the European market. He estimated the world market to be approximately two to three times larger.

Table FZK.2
Projected European Superconductivity Market (M = million)

Application	2010	2020
Generators	$100 M	$200 M
Transformer and Cables	$600 M	$3,000 M
Storage (Flywheels and SMES)	$400 M	$1,500 M
Fault-current limiters	$600 M	$1,700 M
TOTAL	**$1,700 M**	**$6,400 M**

U.S. estimates, obtained from EPRI, for all of the electric power applications are given for comparison:

$600 million (2000), $3,300 million (2010), and $9,600 million (2020)

These U.S. estimates do not appear to be inconsistent with the CONECTUS study and combined with the European figures present a more conservative market forecast than the ISIS study. As noted in the Japanese site reports, some of the panel’s Japanese hosts also expressed the view that the ISIS forecast was highly optimistic.

Site: **Siemens**
ZFE T EP 4
P.O. Box 32
D-91050 Erlangen, Germany
http://www.siemens/de/

Date Visited: 12 June 1996

WTEC Attendees: R.D. Blaugher (report author), D. Larbalestier

Hosts: Dr. H.-W. Neumuller, Manager, Superconductivity Program,
Siemens Research and Development

BACKGROUND

At the "Statusseminar" in Cologne (see site report on Statusseminar), it was acknowledged that Siemens has the largest SC research activity in Germany, which results in its having a significant influence on ongoing German programs involving both materials and electric power applications. Siemens, in fact, is the only large industrial company in Germany seriously pursuing SC materials research and electric power application development with emphasis on HTS. As a result and much to its credit, Siemens has developed strong collaborative relationships with other German companies, the national laboratories, and the universities. Some collaborations and joint projects are a direct result of Ministry of Education, Science, Research, and Technology (BMBF) funding for many of the projects. Siemens has also teamed with other companies and groups located outside Germany on selected projects. Siemens has a long history related to superconductivity research and has been a major past participant in LTS research and more recently on HTS development. Unlike many German companies that have stopped all HTS-related work, such as Daimler-Benz, AEG, and ABB (Germany), Siemens continues with a strong commitment to HTS research and development.

Siemens has 1,111 people at the R&D Centers in Erlangen and Munich with an overall budget of ~$260 million, representing ~7% of the total company revenue. Its R&D headcount is down from 1,250 in 1993 and its peak of 1,500 in 1990. Siemens is organized into 15 business groups that support and fund projects at the R&D centers. Projects at the centers are driven by the company, with ~65% of project funding coming directly from the business groups and external institutions such as BMBF. The remaining projects are funded from a corporate research pot contributed by the business units that covers approximately 35% of the total R&D budget. These jointly funded projects are more basic and innovative in their technical content. Funding for the "applied" projects must be directly provided by the business units. Several years ago, the percentage of "corporately funded" R&D was approximately 70%, with the remaining 30% for projects jointly funded by the business units and corporate research. The policy at the time of the WTEC team's visit was that all R&D personnel had to derive their salaries from a business-unit-related project.

The superconductivity effort at Siemens is almost completely devoted to HTS. The primary projects are directed at the power cable and fault-current limiter with a staff of around 25 and an annual budget, including salaries, of ~ $7.8 million, provided by the Power Transmission and Distribution Group and BMBF funding. This budget and staff are thought to be fairly stable with no forecasted near-term changes in personnel or projects. The HTS effort at Siemens involves both applications and materials work that is closely integrated with the specific requirements for the applications. Siemens closely supports the commercial effort at Vacuumschmelze with R&D of the Bi-oxide conductors and other oxide materials such as thick-film YBCO. Any commercialization for any of the oxide superconductors would be transitioned to Vacuumschmelze.

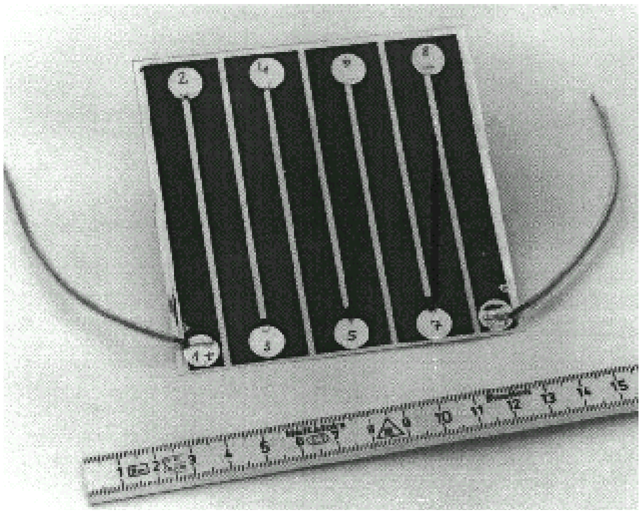
CURRENT HTS RESEARCH AND DEVELOPMENT

The two major research activities at Siemens related to this WTEC study are focused on HTS underground transmission cables and fault-current limiters. The joint funding for these two projects has been ~$27 million over the past three years. The Siemens cable division has funded 50% of this, with the balance from BMBF. Siemens has fabricated and tested short (10 m) cable lengths and is planning longer lengths > 30 m with a major (three-phase) demonstration planned by 2002. This latter program would construct a prototype at 110 kV at lengths >30 m and would be funded by BMBF. The terminations for this cable have been designed, and loss measurements were underway at the time of the WTEC team's visit. Siemens management feels that long lengths of 8-10 km would be needed for commercialization at 110 kV with a 1,000 MVA rating. This cable should offer an efficiency improvement over conventional cable, with a 30-year lifetime and the ability to use existing rights of way. Expansion of transmission within Germany is extremely difficult; it is nearly impossible to obtain new rights of way for overhead transmission. In the 400 MVA range, the SC cable is competing with "extruded" cable, which is showing good progress.

Research on superconducting fault-current limiters (SCFCL) using HTS thick-films is the other major Siemens activity. Siemens is currently evaluating a resistive approach using YBCO "oriented" thick films deposited as a meander line on a ceramic substrate such as YSZ or Sapphire. The SCFCL program is part of a joint project between Siemens Power Transmission and Distribution and Hydro-Quebec (Canada) on HTS for power transmission systems. Hydro-Quebec is studying an inductive approach for a SCFCL similar to the ABB-Baden "shielded core" design.

The Siemens resistive design for an SCFCL is attractive, since it provides a fairly simple approach with no reactive power penalty. The "resistive" SCFCL is designed to rapidly normalize during a transient, with a sufficient increase in resistance to limit the current rise and completely recover to the superconducting state during the time the circuit breakers are clearing the fault. YBCO thick films are especially attractive, because appreciable resistance can be obtained for a fairly short line. The use of a coil of Bi-2223, for example, would be unattractive, since the Ag sheath would require a long length of wire for an acceptable normal state resistance. The transport properties for the film, however, are important; thus, a high J_c is required for a practical design. The Siemens program is exploring a number of deposition techniques to evaluate the ability to obtain high J_c for a large area deposition. Siemens is internally developing large-area "oriented" YBCO deposition using ion beam assisted laser ablation. Outside activities, also on YBCO, are being pursued by R. Wordenweber at Julich using magnetron sputtering and by H. Kinder at the Technical University of Munich using coevaporation. The laser ablation system at Siemens had been previously used to explore the use of IBAD/YBCO for forming YBCO on a Hastelloy substrate using a continuous process. The best results obtained for a 15 cm length showed nominal J_c of 2×10^4 A/cm^2. This effort subsequently was terminated in favor of the current large area deposition for the SCFCL. In retrospect, the WTEC team's hosts at Siemens indicated that their earlier work may have suffered because the ion beam was too narrow. They also commented it was easier to orient YSZ on Hastelloy than on polycrystalline YSZ.

Siemens is currently testing YBCO films prepared by different deposition techniques using either pulsed laser ablation, magnetron sputtering, or coevaporation onto 10 cm x 10 cm YSZ or sapphire substrates. Figure Siemens.1 shows one of these films, deposited by coevaporation. Recent tests on a magnetron sputtered film showed fairly attractive results: application of a 270 A fault-current initiated resistance within ~20 ms, limiting the current to ~26 A, which is 2-3 times the nominal current of ~9 A_{rms}. After circuit breaker interruption to simulate fault clearing, the "resistor" recooled to the superconducting state within one second, which is impressive. The Siemens resistive design is thus quite promising and will be extended to larger power levels of 100 kVA using between 5-20 YBCO modules with either 10 cm x 10 cm or 20 cm x 20 cm dimensions.



Highest values for YBCO on PSZ with biaxially aligned YSZ buffer

Sample size:
A = 10 x 10 cm^2

YBCO film thickness:
d = 1.4 µm

Critical current:
I_c(77 K) = 8.6 A

Critical current density:
J_c(77 K) = 6.1 x 10^4 A/cm^2

Nominal switching power:
P_{nom}/A = 40 W/cm^2

Fig. Siemens.1. YBCO thin-film superconducting fault-current limiter: YBaCuO film on polycrystalline zirconia deposited by thermal coevaporation (Siemens).

A flywheel energy storage activity is also under consideration at Siemens. A 10 kWh (2 MW) size is planned for future construction. This flywheel would be a “stacked” design using HTS/permanent magnetic bearings. A composite, rather than steel, flywheel is planned with a diameter of ~ 80 cm. Large, above-ground, installation with appropriate protection is favored, as opposed to below-ground excavation, due to the projected lower installation expense. It is expected that large energy delivery at >20 MW would most likely experience some problems with respect to heating of the motor/generator. Flywheels appear attractive for railway applications, combined with regenerative braking for charging. Siemens is also conducting studies using flywheels for spinning reserve. The 10 kWh development program is currently being discussed with the business groups to generate interest and a possible teaming arrangement. SMES continues to be of interest but is thought to be too expensive. Siemens is also looking at a 10 MW SC transformer for high-speed trains, which would be developed jointly by the French and Germans.

GENERAL OBSERVATIONS

Dr. Neumuller commented on the projected market for electric power applications using HTS components. HTS current leads are now a commercial reality and can be purchased from a number of manufacturers: Hoechst, ASC, etc. He feels the next serious introduction will be flywheels by 2002 at 10-100 kWh, followed by SC fault-current limiters and transmission cables. Prototypes of SCFCL should be available by 2005, with full commercialization expected ~10 years later. High field, high density SMES would then follow, along with transformers at a ~ 200 MVA rating. HTS SMES would require a “composite conductor,” with thousands of amperes capacity and low ac losses to minimize heating for multiple charge/discharge cycles. He indicated that Siemens was not considering work on SC generators, which he felt was not influenced by HTS, due to the lack of a significant efficiency improvement for operation at ~20 K rather than at liquid helium (4.2 K) temperature.

Neumuller thought that International Superconductivity Industry Summit (ISIS) market estimates are extremely optimistic, that a number closer to 10% of ISIS projections is reasonable. ISIS estimates the entire world market for superconductivity, which includes electronics, power applications, transportation, medical, etc., to be ~$15 billion by year 2000, nearly $75 billion by year 2010 and nearly $250 billion by 2020. The current market for superconductivity that is driven by the medical (MRI) and other magnets was estimated at ~ $2 billion in 1995. The collective market growth for superconductivity should thus be closer to $10 billion by 2010 and double that to ~$20 billion in 2020, which is nearly identical with the European estimate (see also the FZK site report). The 1996 entire world market for switchgear, by comparison, was ~$10 billion.

Site: **Statusseminar**
Supraleitung und Tieftemperatur-technik
Cologne, Germany

Date Visited: 10-11 June 1996

WTEC Attendees: R.D. Blaugher (report author), D. Larbalestier

Hosts: Dr. Bernd Himmerich, VDI Technologiezentrum, Physikalische-Technologien
R. Mann, VDI Technologiezentrum, Physikalische-Technologien

BACKGROUND

Following discussions with Prof. Dr. Herbert Freyhardt (University of Gottingen) and the organizers of the Statusseminar, David Larbalestier and R.D. Blaugher were subsequently invited to attend this meeting and asked to present overviews of U.S. activities in HTS power applications and conductor development. The Statusseminar was organized to provide an assessment of recent progress on the German federally funded program on high temperature superconductors and related low temperature technology. The VDI Technologiezentrum Physikalische-Technologien (Drs. B. Himmerich and R. Mann) organized this meeting on behalf of the Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie (BMBF), i.e., German Federal Ministry for Education, Science, Research, and Technology. MinR. Dr. J. Bandel was the representative from the BMBF for the superconductivity program and at the Statusseminar provided the opening welcome and comments on the purpose of the meeting. This meeting, called the “5th Statusseminar” on “Supraleitung und Tieftemperatur-technik” was held in Cologne, Germany, on June 10-11, 1996.

The meeting was attended by over 200 researchers from the German universities, industries, and national laboratories involved in power-related and electronic research using superconducting components. The first day was devoted to HTS power applications and related materials research on conductors and melt-processed YBCO. The second day covered primarily HTS electronics and related materials and some refrigeration activities in support of the electronics effort. The format for each day was fairly similar: each morning and part of the afternoon was devoted to a series of 20-30-minute plenary talks, followed by a two-hour technical poster session combined with industrial exhibits. The meeting was then reconvened for a panel discussion, the panel being comprised of the plenary speakers to allow audience questioning and additional input to the plenary presentations. The entire day’s session was then concluded with a summary presentation providing some key observations and general remarks. The first day, “Tageszusammenfassung,” was provided by Prof. Dr. Peter Komarek from the Forschungzentrum Karlsruhe (FZK).

The opening comments on the first day from MinR. Dr. Bandel were to some degree very similar to those expressed by his counterparts in the U.S. federal agencies and provided some perspective on the history and prospects for future German government funding on HTS. “Following the discovery of HTS in 1986, which presented a highly optimistic outlook for SC, it was quickly realized that this enthusiasm must be moderated by a consistent effort leading to technological development of these difficult ceramic materials.” Bandel indicated that good progress has been made, which raises the prospects for approval of a new five-year program on HTS. He expected Ministry approval of the new program on HTS at ~DM 40 million/yr. (~$27 million @ DM 1.5/$) when the current one expires in 1997. (Note: with the industrial cost share, the total effort would be ~DM 60 million/yr.)

A major effort on HTS that provided funding to industries, universities, and national laboratories, initiated by the Federal Republic of Germany in 1992, was to be completed in June 1997. This five-year program was funded at ~ DM 40 million for the first year and at DM 37-40 million for the subsequent four years. The BMBF funding that goes to industry requires a 50% cost-share for the large multinational companies. Universities are normally funded at a full 100%. The BMBF funding for the national laboratories mainly goes to Karlsruhe and Julich, in the amount of ~ DM 6 million/yr. The university salaries for the professors are usually paid by the universities, which thus compliment the BMBF support. In contrast to the U.S. DOE program, the BMBF provides nearly half (~ DM 20 million) of the total program to the universities. Additional national laboratory funding for SC comes from other federal sources like the Bavarian Superconductive Initiative and the Lower Saxony Partnership, which includes companies like Solvay GmbH and utilities. Both provide support that is mainly non-material-related. The ministry not only encouraged but directed participants to collaborate under the BMBF program, which thus promoted university/industry/national lab joint programs. An example of this joint collaboration is the Siemens fault-current limiter program with Prof. Kinder (Technical University of Munich) and Prof. Wordenweber (Forschungzentrum Julich) providing materials support to Siemens on YBCO thin-film processing. The competition for BMBF funding, which is highly intensive between the universities, industry, and national laboratories, has, nevertheless, led to extremely strong collaborations that have benefited all parties and significantly advanced the applications development. The implementation of interdisciplinary efforts between the universities and industries for demonstration of HTS prototypes will be one of the main topics for future emphasis and funding by the BMBF.

Bandel was followed by Dr. M. Kleimaier from RWE Energie AG, the largest electric utility in Germany, who provided some very important perspectives on the consideration of the use of superconductivity within the electric power system. RWE has been fairly active in collaborating on superconductivity-related research on power applications. RWE has recently evaluated, with Siemens, the economics and technical prospects for SMES on the electric power system. RWE has also evaluated the use of SC fault-current limiters with Siemens, American Superconductor, and others. RWE is currently part of the flywheel effort with Siemens and FZK providing utility guidance on the application. Kleimaier's talk, which was essentially the keynote address, was entitled "The Application of Superconductivity to the Energy Technologies — Its Possibilities for Usage and Market Opportunity." He presented some opening viewgraphs that indicated the importance of the classical work on improving motors/generators, transformers, and transmission cables, and the recent new applications on flywheels, SMES and fault-current limiters.

Kleimaier argued that success in introducing a new technology to the electric utilities is dependent on realization of a cheaper, more efficient solution than the conventional competing technology. In particular for superconductivity applications, there must be a compelling argument with respect to need, i.e., increase in load, demand for replacement of existing components, etc., and the ability to easily integrate this "new" component into the electric power system. The "new" superconducting component, moreover, must meet a fairly stringent list of utility requirements and show some unique operational advantage over conventional technology in order to be even considered. These requirements cover all of the typical electric utility specifications outlining voltage, current, ac losses, reliability, operational performance and servicing, and basic logistical factors such as size and weight.

A comparison of the advantages and disadvantages for the classical applications, i.e., motors/generators, transformers, and cables, showed the usual expected improvements in efficiency, reduced size and weight, and increased steady state and transient stability. Other unique advantages were also cited:

- for generators, lower synchronous reactance, which would improve static and transient stability
- for transformers, oil free construction and potential current limiting capability
- for cables, the capability for higher power levels at lower voltages, no heat input into the ground or ambient containment, and no external field for a coaxial design.

The stated disadvantages for the respective applications were

- SC generators would only be economical at "high" MVA levels, which is contrary to current market demand for lower-power units
- cables also would only be economical at high power levels, which would create difficulty in accommodating any outage, i.e., would reduce ability to shift load during down time, which is expected to be longer than conventional maintenance and repair

- SC transformers would require higher maintenance, require special cooling of the iron core, and may show higher losses under reduced load conditions.

Kleimaier did not comment on the merits of flywheel storage but indicated that the high cost for SMES, especially for the smaller sizes, would limit serious consideration of magnetic storage technology. The ability of SMES to deliver fast response, high power for short times, and "repetitive cycling" capability was cited as its major advantage. RWE, as noted earlier is, nevertheless, deferring further work on SMES in favor of flywheel technology.

SC fault-current limiters have a fairly long list of advantages, with possible scenarios for use within the electric power system, such as improved voltage quality, ability to utilize present distribution systems, and design of new installations with lower short circuit currents. The cited disadvantages are nominal: the need for improvements in the HTS conductor, ac losses, and higher resistance matrix.

Kleimaier summarized the major limitations for superconducting technology:

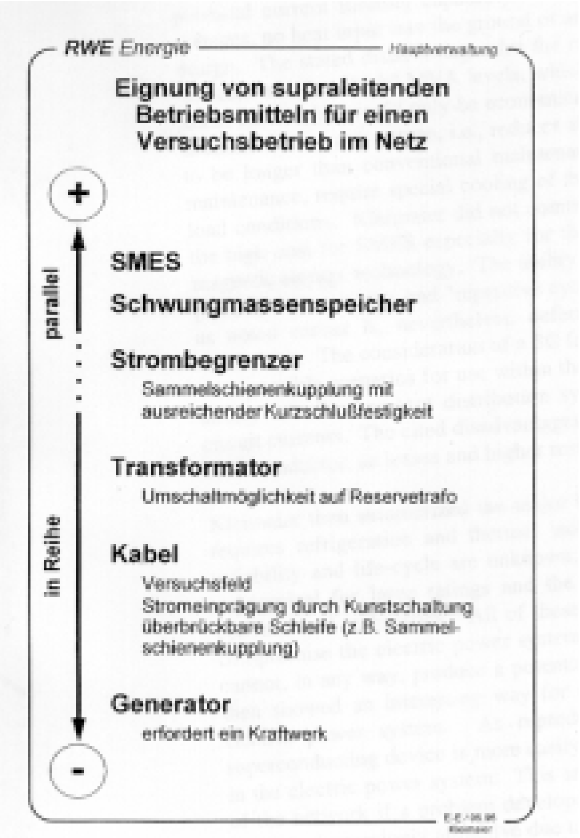
- complexity — requires refrigeration and thermal isolation
- new problems for installation and maintenance — reliability and life-cycle are unknown
- economics — SC applications almost universally are only economical for large ratings and the initial investment cost may be significantly higher than conventional technology

All of these factors, collectively, cannot lead to a situation that might compromise the electric power system, i.e., use of an SC component in the electric power system cannot, in any way, produce a potential negative influence or weakness in the system.

Kleimaier showed an interesting way to consider the possible usage of an SC component in the electric power system. As reproduced in Fig. Stat.1, Kleimaier's assertion is that use of a superconducting device is more easily considered and tested if the device can be placed in parallel in the electric power system. This arrangement would allow the device to be easily switched out of the network if a problem develops. The installation of transformers, cables, and generators are thus decreasingly attractive due to their requirement for "serial" installation, with the generator requiring a power station for its test and evaluation.

Kleimaier then concluded with these key observations: integration of SC components within the electric power system must be easily accomplished. Except for current limiters, profitable use of SC devices requires high power levels. Even with successful prototype demonstrations, the market in Europe will develop slowly, except for current limiters. Superconducting current limiters appear to have the most potential, since there is no viable alternative technology. Finally, confidence in the new SC technology will only occur with successful testing under "utility" conditions that are eventually carried out within the electric power system.

The other important plenary presentations were by Dr. J. Bock, Hoeschst AG, who outlined progress on HTS high current leads, and by Dr. H.W. Neumuller, who reviewed the Siemens effort. The latter presentation, for the most part, is discussed in the site report for the visit to the Siemens Laboratory at Erlangen. The presentations by Larbalestier and Blaugher were both fairly well received, as indicated by the high number of questions and lengthy discussion that followed each presentation.



RWE Energie — Hauptverwaltung

Eignung von supraleitenden Betriebsmitteln für einen Versuchsbetrieb im Netz

+

parallel

SMES

Schwungmassenspeicher

Strombegrenzer

Sammelschienenkupplung mit ausreichender Kurzschlußfestigkeit

Transformator

Umschaltmöglichkeit auf Reservetrafo

in Reihe

Kabel

Versuchsfeld

Stromeinprägung durch Kunstschaltung

überbrückbare Schleife (z.B. Sammelschienenkupplung)

Generator

erfordert ein Kraftwerk

-

Fig. Stat.1. Evaluation of a superconducting device (Kleimaier).

Site: **Vacuumschmelze (VAC)**
P.O. Box 23 53
D-63450 Hanau, Germany

Date Visited: 11 June 1996

WTEC Attendees: R.D. Blaugher (report author), D. Larbalestier

Host: Dr. Helmut Krauth, Deputy Director, Vacuumschmelze GmbH
Superconductor Division Gruener Weg 37

BACKGROUND AND CURRENT HTS RESEARCH AND DEVELOPMENT

Following the realization of Type II superconductors in 1962, Vacuumschmelze GmbH was one of the first companies to initiate, in 1966, the production of conventional low-temperature superconducting (LTS) wires such as Nb-Ti and Nb_3Sn. Vacuumschmelze (VAC) is currently the world's third leading manufacturer of conventional LTS wires, behind Intermagnetics General Corp. (IGC) and Oxford. Most of VAC's LTS production, much like that of IGC and Oxford, is for the MRI market. VAC is only interested in the SC wire or tape market, with no past and no expressed future interest in the fabrication of SC devices such as magnets, leads, etc. VAC, which is fully owned by Siemens, is nevertheless free to sell (or buy) wire from anyone. This "free market" ability would also apply to VAC's HTS conductor products. VAC has been active in HTS wire development since the initial HTS discovery in 1986. The HTS research at VAC, in fact, provided one of the major HTS wire achievements when Heine, Tenbrink, and Thoener published their results (1989) on powder-in-tube Bi-2212 wires that showed high current density of 1.5×10^4 A/cm^2 at 4.2 K in a magnetic field of 26 T, which exceeded the performance of all LTS conductors at this magnetic field level. These results excited the SC community and precipitated the expansion of HTS wire development programs worldwide, particularly in the United States and Japan.

VAC is one of the world's leading producers of special metallic materials, with broad interests in a wide range of products beyond superconductivity. VAC, which started in 1923 to melt alloys under vacuum, has grown to have a product range of over 200 special alloys covering a large number of applications. VAC employs approximately 2,000 people and has an annual revenue of ~ DM 420 million ($300 million). The main works and head office for VAC is in Hanau, Germany, which is roughly 25 km from the Hauptbahnhof of Frankfurt. The superconductivity effort at VAC, which is also housed within the Hanau facility, involves approximately 60 people, principally in LTS manufacturing, with about 6 people devoted to HTS development. Dr. Helmut Krauth directs all of the superconductivity efforts at VAC. Superconductivity revenues for both LTS and HTS total around $15-20 million/yr., which represents 5-7% of VAC total sales.

Krauth was very clear on the ground rules for continued operation of the superconductivity effort at VAC: "It must operate in the black." In fact, due to previous poor years, it was heavily scrutinized by Siemens as to its future existence. Following this evaluation, the decision was made to continue the HTS operation in close cooperation with the research group at Erlangen. The Siemens HTS effort, which is ~3x larger than the VAC group, is currently providing support on Bi-2223 production, which will eventually be completely carried out at Hanau starting in late 1997. Siemens is providing support to VAC on sheath alloy development for improved ac losses and mechanical strength. At the time of the WTEC visit, VAC was expanding its facilities to accommodate the production of Bi-2223 tape at longer lengths of many km, up from the ~500 m lengths that it had been able to produce previously. VAC fabricates round Bi-2223 wire that is delivered to Siemens, where it is then rolled and heat-treated. The nominal long-length current density of the VAC/Siemens wire is above 2.0×10^4 A/cm^2 at 77 K, H(0), with short lengths approximately a factor of two higher in J_c. VAC, in parallel with the Bi-2223 scale-up, will continue to produce Bi-2212 tape. The primary applications and market potential for the two bismuth compound conductors are as follows:

- Bi-2212 will be used for magnets operating at very high fields (10-25 T) in liquid helium, with a high field magnet market expected three to four years out
- Bi-2223 will be used for energy applications operating at higher temperatures

VAC management expects that the HTS market may develop in about 10 years, with transmission cables and transformers as the first major applications. HTS conductor will be needed near-term (2002) for transmission cable demonstrations. The high Ag content and high processing expense for the present PIT approach is a major cost driver, especially for the Bi-2223 conductor. A more practical conductor with less Ag is needed long term.

VAC has no current internal plans for processing or developing the other oxide materials. The YBCO coated conductor work, i.e., IBAD, etc., is being pursued at Siemens, which is emphasizing large area YBCO depositions for fault-current limiters. VAC, through Siemens, will follow this activity and when appropriate will enter the market. VAC similarly has no effort on Tl or Hg compounds and is depending on the German universities, such as Freyhardt's work at Gottingen, for input on the potential of these materials. The WTEC team's hosts at VAC stated that they wish to and intend to remain a major supplier of superconducting wire and tape in both the LTS and HTS markets. It should be possible for VAC to maintain this position with the continued interest and support from Siemens, which provides a unique relationship between an SC wire manufacturer and end user. The continued support of the German government (BMBF) is also important in maintaining the essential funding for HTS research at Siemens and in turn VAC. The major part of the HTS effort at VAC is performed within a BMBF-funded project lead by Siemens that includes VAC, FZK Karlsruhe, and IFW Dresden as the principal partners. Additional support on this program is also obtained from other German research institutions. The Bi-2223 tape for the Siemens (3,000 A) cable demonstration was supplied by VAC with assistance from IFW Dresden on some of the thermomechanical treatments.

APPENDIX E. PARTIAL LISTING OF WORLD WIDE WEB HOMEPAGES FOR SITES VISITED BY THE PANEL

JAPAN

CRIEPI — http://criepi.denken.or.jp/

Chubu Electric Power Co., Inc. — http://www.chuden.co.jp

Fujikura — http://www.fujikura.co.jp/fujikuev.htm

Furukawa — http://www.furukawa.co.jp/english/cover.htm

Hitachi Research Lab — http://www.hitachi.co.jp/index.html

*** International Superconductivity Technology Center (ISTEC)**
http://www.sendai.kopas.co.jp/ISTEC [/ISTEC/index-E.html for English version]

KEK — http://www.kek.jp/

Kobe Steel — http://www.kobelco.co.jp/indexe.htm

MELCO — http://www.melco.co.jp:80/index_e.htm

NRIM — http://www.nrim.go.jp/

NEDO — http://www.nedo.go.jp/index-e.html

*** RTRI** — http://www.rtri.or.jp/

SEI — http://www.sei.co.jp

Tokai University — http://www.u-tokai.ac.jp/English/index.html (only general university info)

TEPCO — http://www.rd.tepco.co.jp/

Toshiba — http://www.toshiba.co.jp/index.htm

University of Tokyo — http://www.appchem.t.u-tokyo.ac.jp/labs/kitazawa/superconductivity/index.html

EUROPE

Forschungszentrum Karlsruhe GmbH — http://www.fzk.de

Siemens — http://www.siemens.de/

* Have the most information about HTS

APPENDIX F. GLOSSARY

AC/ac	Alternating current
AEG	Allgemeine Elektrizität Gesellschaft
AIST	(Japan) Agency of Industrial Science and Technology, a part of MITI
AML&P	(U.S.) Anchorage Municipal Light and Power (utility)
ANL-CFTF	Argonne National Lab, Coal-Fired Test Facility
ASC	American Superconductor Corp.
ASD	Adjustable-speed drive
B&W	(U.S.) Babcock and Wilcox
Bi-2212	$Bi_2Sr_2CaCu_2O_x$
Bi-2223	$(Bi, Pb)_2Sr_2Ca_2Cu_3O_x$
BICC	British Insulated Callendars Cables, Ltd., a major British wire and cable producer
BMBF	(Germany) Ministry of Education, Science, Research, and Technology
BNL	(U.S.) Brookhaven National Laboratory
BRITE EuRAM	Basic Research of Industrial Technologies for Europe, European Research on Advanced Materials program
BSCCO-2223	$(Bi, Pb)_2 Sr_2Ca_2Cu_3O_x$
CEC/ICMC Meeting	Cryogenic Engineering Conference/International Cryogenic Materials Conference
CERN	European Laboratory for Particle Physics (located on French/Swiss border)
CIC	Cable-in-conduit
CONECTUS	Consortium of European Companies (determined to use superconductivity)
CRIEPI	(Japan) Central Research Institute of the Electrical Power Industry
CRT	Composite reaction textured (material)
CSAC	Council on Superconductivity for American Competitiveness (U.S.)
CVD	Chemical vapor deposition
dc	Direct current
DESY	Deutsches Electronen Synchrotron (Lab)
DOE	(U.S.) Department of Energy
EERE	Office of Energy Efficiency and Renewable Energy (within DOE's Office of Energy Management)
EPRI	(U.S.) Electric Power Research Institute (consortium of electric utilities)
ETL	(Japan) Electrotechnical Laboratory, MITI
Euratom	European Atomic Energy Community, established at the same time as the European Community
FCL	Fault current limiter
FRP	Fiber-reinforced plastic
FWHM	Full width at half maximum
FZK	Forschungzentrum Karlsruhe
GM	Gifford McMahon (refrigerator)
H	Henry (unit for inductance)
Hastelloy	Trade name of commercial Ni-based high temperature alloys
HEP/DOE	Office of High Energy and Nuclear Physics, U.S. Department of Energy
H_{OP}	Operating magnetic field
HTS	High temperature superconductor/superconductive/superconductivity
I	Current expressed in amps
I^2R	Joule heating, the product of the current squared times the resistance of a conductor
IBAD	Ion beam assisted deposition
I_c	Critical current of a superconductor, the maximum amount of current that can flow below a fixed electric field or resistivity criterion
ID	inner diameter

I_{FL}	I = current, FL = full load / Full load current
IGC	(U.S.) Intermagnetics General Corp.
IPP	Independent power producer
IR	Current times the resistance of a conductor; equals the voltage drop along the conductor
IRD	International Research and Development Co., Ltd.
I_{SC}	I = current, SC = short circuit
ISIS	International Superconductivity Industry Summit
ISTEC	(Japan) International Superconductivity Technology Center
ITER	International Thermonuclear Experimental Reactor
I-V	Current-voltage
JAERI	Japan Atomic Energy Research Institute
J_c	Critical current density
J_e	Engineering critical current density (current/total conductor cross-section)
JEOL	Japan Electron Optics, Ltd., a major supplier of electro-optical, analytical (including NMR spectrometers) and medical equipment
JR	Japan Railway Group of passenger and freight rail companies
JRDC	Japan Research Development Corporation (recently renamed JST)
JST	Japan Science and Technology Corporation (funded by STA)
KEK	(Japan) National Laboratory for High-Energy Physics
KEPCO	(Japan) Kansai Electric Power Co.
LANL	Los Alamos National Laboratory
LHC	Large Hedron Collider at CERN
LL	Load losses
LLNL	(U.S.) Lawrence Livermore National Laboratory
LPE	Liquid phase epitaxy
LTS	Low temperature superconductor/superconductive/superconductivity
Maglev	Magnetic levitation project of Japan's Railway Technical Research Institute
MEG	Magnetoencephalography
MELCO	(Japan) Mitsubishi Electric Co.
M-G	Motor-generator
MHD	Magnetohydrodynamic
MITI	(Japan) Ministry of International Trade and Industry
MOCVD	Metallorganic chemical vapor deposition
MOE	(Japan) Ministry of Education, Science, and Culture
MOV	Metal oxide varistor
MPI	(Germany) Max Planck Institutes
MPMG	Melt powder melt growth
MRI	Magnetic resonance imaging
Nd-422	$Nd_4Ba_2Cu_2O_x$
NEDO	(Japan) New Energy and Industrial Technology Development Organization (funded by MITI)
NIFS	(Japan) National Institute of Fusion Science (Nagoya)
NLL	No-load loss
NMR	Nuclear magnetic resonance
NREL	(U.S.) National Renewable Energy Lab
NRIM	(Japan) National Research Institute for Metals
OD	Outer diameter
OFE/DOE	Office of Fusion Energy, U.S. Department of Energy
OST	(U.S.) Oxford Superconducting Technology
PCS	Persistent current switch
PCS	Power conditioning system
PIT	Powder in tube (conductor)
PLD	Pulsed laser deposition

p-YSZ	Polycrystalline yttrium-stabilized zirconia
QMG	Quench melt growth
RE	Rare earth element (such as La, Nd, Sm, Eu, Gd, etc.)
RE-123 oxides	123 compound formed with a rare earth instead of yttrium
rf	Radio frequency
rms	Root mean square
RWE	(The largest German utility)
SBIR	Small business innovative research program, U.S. government
SC	Superconductivity
SC/PM	Superconductor/permanent magnet (assembly)
SCFCL	Superconductive fault current limiter
SFQ	Single flux quantum
SI	(U.S.) Superconductivity, Inc.
SMES	Superconducting magnetic energy storage
SPI	(U.S., DOE) Superconductivity Partnership Initiative (focused on systems technology)
SPTL	Superconducting power transmission line
SQUID	Superconducting quantum interference device, a sensitive magnetic sensor
SRL	(Japan) Superconducting Research Laboratory — part of ISTEC
SSC	Superconducting Super Collider Project (U.S., now cancelled)
STA	(Japan) Science and Technology Agency
Super-GM	(Japan, administered by NEDO) Engineering Research Association Project for Superconductive Generator Equipment and Materials
T	Tesla as a unit for magnetic flux density; temperature when used as a symbol or abbreviation
T_c	Superconducting critical temperature: maximum temperature at which a material exhibits superconduction properties
TEM	Transmission electron microscope or microscopy
TEPCO	(Japan) Tokyo Electric Power Co.
Tl-1223	$(Tl, Pb)(Ba, Sr)_2Ca_2Cu_3O_x$
VAMAS	Versailles Project on Advanced Materials and Standards, includes standardization of testing and evaluation methods for low temperature superconductors
XLPE	Cross-linked polyethylene (industry designation for dry insulated high voltage lines)
Y-123	$YBa_2Cu_3O_x$ (see also YBCO)
Y-211	Y_2BaCuO_5
YBCO	$YBa_2Cu_3O_{7-\delta}$ (see also Y-123)
YSZ	Yttrium-stabilized zirconia
Z	Impedence (complex [ac] impedance of a circuit or component consisting of a resistive and a reactive part)