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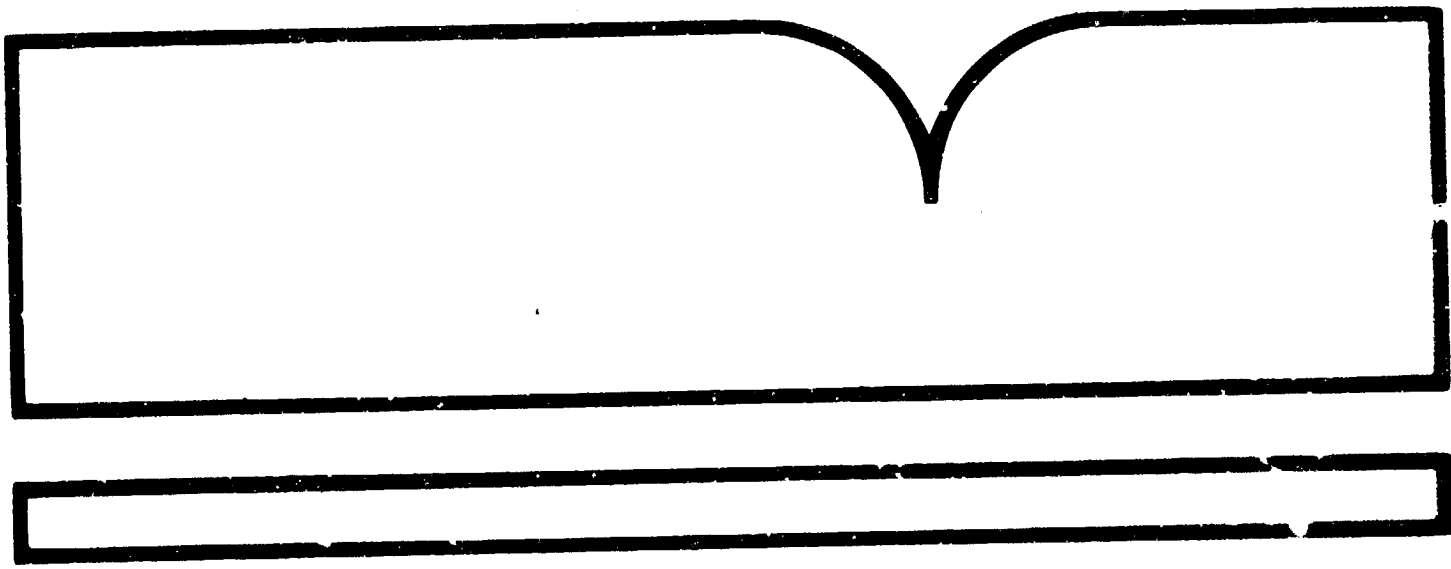
JTEC (Japanese Technology Evaluation Center) Panel
Report on High Temperature Superconductivity in Japan

Loyola Coll., Baltimore, MD

Prepared for:

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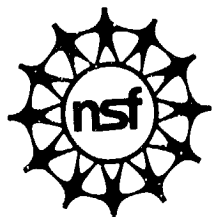
Nov 89



JTEC Panel Report on High Temperature Superconductivity in Japan

Abstract

The Japanese regard success in R&D in high-temperature superconductivity as an important national objective. Japanese scientists and non-scientists alike share a high level of optimism and enthusiasm about the field, and feel that important practical benefits will be realized from high-temperature superconductors by the start of the 21st century. One indicator of the Japanese commitment to the field is the fact that the number of Japanese professional researchers in superconductivity is comparable to the number in the United States. This document provides the results of a detailed evaluation of the current state of Japanese high-temperature superconductivity development. The analysis was performed by a panel of technical experts drawn from U.S. industry and academia, and is based on reviews of the relevant literature and visits to Japanese government, academic and industrial laboratories. Detailed appraisals are presented on the following: Basic research (including new materials structural properties, transport properties, thermodynamic properties, optical properties, electronic structure, magnetic properties); superconducting materials (including new superconducting phases, high T_C oxide superconductors, organic superconductors, heavy fermion superconductors); large-scale applications (maglev trains, superconducting generators, superconducting magnetic energy storage, advances in low T_C conductors, high magnetic field research); processing of superconducting materials (including monolithic conductors, wires, tapes, fibers, thick films); superconducting electronics and thin films, (low T_C integrated thin film processes for Josephson technology; low T_C digital circuits; low T_C analog devices and circuits; high T_C thin films; high T_C devices). In all cases, comparisons are made with the corresponding state-of-the-art in the United States.



Japanese Technology Evaluation Center

JTEC

JTEC Panel Report on

High Temperature Superconductivity In Japan

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November 1989

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JAPANESE TECHNOLOGY EVALUATION CENTER

- SPONSOR** The Japanese Technology Evaluation Center (JTEC) is operated for the Federal Government by Loyola College to provide assessments of Japanese research and development (R&D) in selected technologies. The National Science Foundation (NSF) is the lead support agency. Other sponsors include the Defense Advanced Research Project Agency (DARPA), the National Aeronautics and Space Administration (NASA) and the Department of Energy (DOE).
- PURPOSE** The JTEC assessments contribute to more balanced technology transfer between Japan and the U.S. The Japanese excel at acquisition and perfection of foreign technologies, but the U.S. has relatively little experience with this process. As the Japanese become leaders in research in targeted technologies, it is essential that the U.S. have access to the results. JTEC provides the essential first step in this process by alerting U.S. researchers to Japanese accomplishments. The JTEC findings can also be helpful in formulating Governmental research and trade policies.
- APPROACH** The assessments are performed by panels of about six U.S. technical experts in each area. Panel members are leading authorities in the field, technically active, and knowledgeable of Japanese and U.S. research programs. Each panelist spends about one month of effort reviewing literature, making assessments, and writing reports on a part-time basis over a six-month period. Most panels conduct extensive tours of Japanese laboratories. To balance perspectives, panelists are selected from industry, academia, and government.
- ASSESSMENTS** The focus of the assessments is on the status and long-term direction of Japanese R&D efforts relative to those in the U.S. Other important aspects include the evolution of the technology, key Japanese researchers and R&D organizations, and funding sources. The time frame of the R&D forecasts is up to ten years, corresponding to future industrial applications in 5 to 20 years.
- LITERATURE** Loyola College provides Japanese literature and translation services to the panelists. Special efforts are made to provide panelists with timely source material, such as informal proceedings from seminars and conferences in the Japanese research community, results from recent technical committee meetings on Japanese national R&D projects, and from contacts at R&D centers in Japanese high technology industries.
- REPORTS** The panel findings are presented to small workshops where invited participants critique the preliminary results. The panel final reports are distributed by the National Technical Information Service (NTIS), 5285 Port Royal Road, Springfield, Virginia 22161. The panelists also present the technical findings in papers and books. All results are unclassified and public.
- STAFF** The Loyola College JTEC staff members help select topics to be assessed, recruit experts as panelists, organize and coordinate panel activities, provide literature support, organize tours of Japanese labs, assist in the preparation of workshop presentations and reports, and provide general administrative support.

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HIGH TEMPERATURE
SUPERCONDUCTIVITY IN
JAPAN

JTEC

1989 study

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Preface

This is the latest in a series of Japanese technology assessments that we have been conducting under the JTEC program since 1984. In 1983 George Gamota convinced me and Bill Finan, my counterpart at the Department of Commerce, that the Nation must do more to monitor Japanese research. The methodology chosen was to use an expert panel to take a snapshot of the status of Japanese research in a critical technology by an intensive study—and to communicate the implications of the Japanese efforts to policy makers in Government and industry. To provide the logistics support we contracted with the Science Applications International Corporation (SAIC).

I will review the studies that are available, but will not attempt to summarize each of their findings in a sentence or two—the full reports are available from NTIS. I will make a few overall comments on our findings at the end.

Our first effort was a series of four panels in 1984 and 1985. We asked David Brandin, then at SRI, International to chair a panel which would take a look at the broad range of computer science. Dale Oxender at Michigan chaired a panel on biotechnology. Jim Nevin at the Draper Laboratory led a group that looked at mechatronics, which the Japanese define as the union of electrical and mechanical engineering—things like robotics and flexible manufacturing systems. Finally we had a group, jointly chaired by Bill Spencer of Stanford and Harry Weider of UCSD, research Japanese progress on non-silicon microelectronics, such as gallium arsenide devices and optical electronics devices.

In 1986 the National Science Foundation took over the role as lead agency, and with additional funding from DARPA, we organized six panels during the next three years. Our telecommunications panel was chaired by George Turin, then Dean of Engineering at UCLA. The group on advanced materials (primarily polymers) was chaired by Jim Economy of IBM. Under Marvin Denicoff of Thinking Machines Inc., our second computer panel took a focused look at parallel architectures, particularly the Fifth Generation Project. This group was the first to include a tour of Japanese laboratories as a formal part of its procedures, which proved to be so illuminating that all subsequent panels have taken a similar trip there. In 1988 George Gamota and Wendy Frieman compiled the results of the first six panels with some cross-cutting observations into the book Gaining Ground: Japan's Strides in Science and Technology, published by Ballinger.

The Japanese ERATO basic research initiative consists of more than a dozen projects intended to foster creativity and cooperation in more basic research, particularly in electronic materials and biotechnology. We appointed joint chairmen, Bill Brinkman of Bell Laboratories and Dale Oxender of Michigan to cover these areas.

Computer aided design and computer integrated manufacture of semiconductors in Japan was studied by a panel under Bill Holton of the Semiconductor Research Corporation. Finally research in advanced sensors was assessed by a panel under Laurie Miller of Bell Laboratories.

By 1989 the project had proven to be successful enough to warrant establishment of a Japanese Technology Evaluation Center at Loyola College under a grant from NSF with additional funding from DARPA, NASA and the Department of Energy. The current phase includes the six panels. High definition television systems have been assessed by a group under Dick Elkus. The present report on superconductivity applications was compiled by a group under Mildred Dresselhaus of MIT. We have a group looking at space and trans-atmospheric propulsion under Charles Merkle at Penn State. Our third computer panel is supporting the implementation of the science and technology treaty signed by President Reagan and Prime Minister Takeshita in Toronto in 1988 by identifying opportunities for joint research in advanced scientific computing. It is chaired by Mike Harrison of Berkeley. Nuclear power generation in Japan is being researched by a panel under Kent Hansen at MIT, and high temperature composite materials are being studied by a group under Judd Diefendorf at Rensselaer.

We have seen Japanese research make great progress over the course of the JTEC studies. In 1984 the conventional wisdom was that the Japanese excelled at acquiring foreign technologies, performing competent applied research to perfect them, and developing manufacturing techniques to make products from them of the highest quality. Our early panels frequently confirmed that model, but began to report centers of excellence in more basic research as well, particularly in areas targeted by the Japanese for long term commitments. Now we are seeing more technologies where the Japanese are using the revenue stream from their favorable balance of trade to strengthen their basic and applied research capabilities. As these investments produce innovations, we in the United States must learn how to better transfer Japanese technologies to the U.S. JTEC can be a useful first step in that process, by identifying areas where the Japanese have the world's best technologies.

Frank Huband

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Executive Summary

To study and assess the state-of-the-art of Japanese R&D in superconductivity, we first prepared a preliminary assessment of the state of the art in the U.S. to form a baseline for our visit to leading centers for superconductivity research in Japan. The visits included 3 university, 11 industrial and 7 government laboratories over a 10 day period. During this time we had an opportunity to interact in depth with the Japanese leaders in superconductivity R&D, as well as many younger, active researchers. On this basis we have prepared detailed appraisals of their basic superconductivity program, materials research, large scale applications, materials processing and electronics applications, including thin film R&D. From these detailed appraisals we draw several conclusions, which are presented below.

- Japan has a deep, long-term commitment to superconductivity R&D in industry, academia and national laboratories.

This commitment is seen in several ways such as the many people involved in superconductivity R&D, comparable in numbers to those in the U.S., though their population is less than half. Several 5-10 year superconductivity projects are in place, sponsored by the four agencies supporting superconductivity research: MITI (Ministry of International Trade and Industry), STA (Science and Technology Administration), Monbusho (Ministry of Education) and JR (Japanese Railway). These projects include the Monbusho Special Project on High Temperature Oxide Superconductors, the MITI International Superconductivity Technology Center (ISTEC) consortium, the MITI Josephson Scientific Computing System project, the JR Magnetic Levitation program, the MITI Superconducting Generator project, the STA Multi-Core Project in Superconductivity, and the STA ERATO (Exploratory Research for Advanced Technology) Quantum Flux Parametron project.

- Because of its perceived scientific and technological importance, superconductivity has been selected as a flagship to show the world that the Japanese can be and are successful in fundamental scientific research.

While the Japanese in recent years have been extremely successful in advanced technology and commercialization, they have been criticized by foreigners for their lesser overall contributions to basic research. To answer this challenge, the Japanese are taking bold steps to enhance their basic research effort in superconductivity through increased support to leading academic groups, the establishment of ISTEK, the strengthening of their infrastructure for basic research and the promotion of personnel exchanges with foreign countries. Whereas the Japanese and U.S. are presently comparable in basic experimental studies and materials research, the Japanese are improving rapidly and competing with us strongly. At the present time, our estimates suggest that the number of Japanese researchers working on the basic science of superconductivity is comparable to that in the U.S.

- The Japanese identify superior materials as the key to success in high- T_c superconductivity research and technology, and are translating this philosophy into a sustained, systematic approach to materials synthesis and processing, including new materials research.

The Japanese have consistently given greater emphasis to materials research, and have been more successful in maintaining a sustained, systematic approach to synthesis and processing. They also have a larger effort in looking for new superconducting materials. Most of their outstanding achievements are related to this systematic approach, which is reinforced by their "top-down" management structure and their appreciation of the people who do materials synthesis, processing and scale-up. The Japanese lead us in their ability to mount sustained, systematic materials R&D programs, and have a better trained work-force to implement such programs. While the "top-down" management system reinforces sustained, systematic research, it may be less conducive to creativity. The Japanese presently are putting more effort into new superconducting materials, especially organic superconductors, which are considered to be an integral part of the Japanese superconducting materials program, and are being studied in many Japanese laboratories.

- In basic science, the interaction between groups in different Japanese organizations in industry, university and national laboratories is not as strong as in the U.S.

While teamwork within an organization tends to be stronger than in the U.S., the interaction between researchers in different Japanese organizations tends to be weaker, especially in basic research. Through government leadership, the Japanese are taking steps to break down these barriers by funding large inter-university programs, establishing R&D consortia such as IS-

TEC, and encouraging strong project-related inter-organizational collaborations which however tend to be in applied areas. Examples of inter-organizational efforts in applied areas are the Josephson Scientific Computing System project and the Multi-Core Project in Superconductivity, the latter aimed at developing high- T_c superconductors to the point of commercialization. Such governmental leadership has demonstrated a number of successful achievements in technology transfer from government laboratories working in close collaboration with industry in the area of both large scale superconducting magnet projects and low- T_c Josephson junction electronics.

- The facilities and infrastructure at Japanese universities for superconductivity research is steadily improving, so that now the best Japanese universities are equipped nearly as well as their American counterparts.

The equipment and facilities for superconductivity R&D in Japanese industry and in their national laboratories are equal or superior to that in the U.S., and are steadily improving relative to the U.S. Although the facilities and infrastructure for superconductivity research in Japanese universities have lagged that in the U.S., the best Japanese universities are now rapidly improving and may soon be on a par with ours. The excellent research opportunities in Japan are starting to attract foreign talent, despite the large social and language barriers.

- The Japanese have developed a strong industrial base for the large scale application of low- T_c superconductivity, through government leadership, and collaborative work at national laboratories, electrical industries and the wire and cable companies.

While consortia are being mounted in the U.S. to enhance technology transfer, the Japanese have already demonstrated successful examples of technology transfer for more than a decade in large scale superconductivity applications. Through government leadership, research and development personnel at the national laboratories (NRIM and ETL), have worked collaboratively through the R&D cycle with electrical industries (Hitachi, Mitsubishi and Toshiba) and with wire and cable companies. These collaborations have produced an impressive array of large magnet systems for magnetic fusion, high energy physics, magnetic levitation, power generation, and magnetic resonance imaging (MRI) applications. Japanese capabilities in superconducting wire for the next generation of magnets (above 15 tesla) significantly exceed capabilities in the U.S. and the gap is widening.

- Low- T_c Josephson digital capabilities at four Japanese laboratories far exceed those at any laboratory in the U.S., while analog superconducting electronics capabilities in the U.S. significantly lead those in Japan.

One overwhelming success of the MITI superconducting electronics project is the low- T_c digital chip technology development, providing a model of significant technology development and transfer through a national laboratory-industrial collaboration. Japan now dominates all digital Josephson technology, and Japanese companies are well positioned for possible future commercialization.

Because of greater U.S. analog superconducting device expertise, U.S. efforts in these devices are well advanced over the Japanese level. Since early high- T_c electronics applications will likely be in analog devices, the U.S. is at present well positioned to lead in these areas. U.S. leadership is threatened, however, if superior low- T_c technology remains the norm in Japan and if the analog device expertise in Japan grows in conjunction with their expanded superconducting thin-film and electronics developments. The Japanese are maintaining strong low- T_c electronics programs as a critical component of their superconducting technology development effort.

Japan and the U.S. are both strong in superconductivity R&D. There are thus many opportunities to work together and learn from each other. Because of the greater emphasis of the Japanese on sustained, systematic materials research, they are offering us strong competition in research and are developing the potential to pull ahead on commercial applications.

Chapter 1

Overview

M.S. Dresselhaus

1.1 Conduct of the Study

The JTEC study was formally initiated at a meeting on March 31, 1989 in Washington at the National Science Foundation. At this meeting the scope of this JTEC study on "High Temperature Superconductivity in Japan" was established and the strategy for carrying out the study was delineated. Each of the JTEC Panel attendees (M.S. Dresselhaus, R.C. Dynes, P.M. Horn, J.K. Hulm, M.B. Maple and R.W. Ralston) was given a topical assignment, and these topics basically correspond to the chapters of this report. At this meeting, the need for an expert in the processing of superconducting materials and for a representative from a national laboratory was identified, leading to the addition of Dr. Rod K. Quinn to this JTEC team. (See Exhibit A.1 of Appendix A for biographical sketches of the JTEC Panel members.) In preparation for our trip to Japan, draft papers were written by members of the JTEC Panel on each of the topical areas of the report, highlighting the state-of-the-art in R&D in the U.S. These draft reports also made contact with the international scene (other than Japan), especially in cases where truly exceptional work was being done elsewhere. These state-of-the-art papers thus formed a frame of reference for the present JTEC study.

Through prior personal knowledge of the JTEC Panel members about superconductivity R&D, through their study of previous reports on Japanese R&D kindly supplied by our staff associates, and through the experience gained from preparing the state-of-the-art summaries mentioned above, a list of Japanese laboratories with significant R&D in high- T_c superconductivity was constructed (see Table 1.1). Dr. Alan Engel, of International Science and Technology Associates, then proceeded to make contacts with the above-listed laboratories.

Table 1.1: Institutions visited for the JTEC superconductivity study

Universities	Institute for Materials Research (Tohoku U.) Institute for Solid State Physics (U. of Tokyo) University of Tokyo
Industries	Fujitsu Furukawa Hitachi (Ibaraki) Hitachi (Kokubunji) Matsushita Mitsubishi NEC NTT (Ibaraki) NTT (Musashino) Sumitomo Toshiba
Government Labs	Electrotechnical Laboratory ISTEC (Nagoya) ISTEC (Tokyo) KEK Miyazaki Maglev Test Site NIRIM NRIM Railway Technical Research Institute

and thus ably arranged our schedule in Japan. Arriving in Japan prior to the JTEC panel, Dr. Engel proceeded to fine-tune our itinerary to arrive at the schedule for the period May 30 to June 10 shown in Exhibit A.2 of Appendix A. The visits included 3 university, 11 industrial, and 7 government laboratories over a 10 day period. During this time we had an opportunity to interact in depth with the Japanese leaders in superconductivity R&D, as well as many younger, active researchers. On this basis we have prepared detailed appraisals of their basic superconductivity program, materials research, large scale applications, materials processing and electronics applications, including thin film R&D. Because of Dr. Paul Horn's scheduling conflict, some of his laboratory visits in Japan were made by his colleague Dr. William Gallagher of IBM, Yorktown Heights, who in practice became a full-fledged contributing member of the team.

After returning to the United States, a draft report was prepared, which formed the basis for the oral report given in the Board Room of the National Science Foundation in Washington on August 1, 1989. Agendas for the meetings on March 31 and August 1 are shown in Exhibits A.4 and A.5 of Appendix A, respectively. Input from the discussants (who formed the JTEC Review Panel, and are listed in Exhibit A.3 of Appendix A) and from other participants at the oral presentation was invaluable in revising the draft report to its present form.

1.2 General Observations

It is the belief of the JTEC Panel that the Japanese regard success in R&D on superconducting materials as an important national objective. Many Japanese feel sensitive to foreign accusations that Japan has not contributed as strongly as the U.S. or western Europe to basic research across broad areas of science. The Japanese have thus selected high- T_c superconductivity as a topic to demonstrate to the world their capability in world class basic research. Although the euphoria of 1987 regarding high- T_c superconductivity has subsided somewhat, Japanese scientists and non-scientists alike share a high level of optimism and enthusiasm about the field, and feel that important practical benefits will be realized from high- T_c superconductors by the start of the twenty-first century.

One indicator of the Japanese commitment to superconductivity is the resource allocation to the field and the speed with which they set their national program in place. Although the population of Japan is less than half that of the United States, it is thought that the number of Japanese professional researchers in superconductivity is comparable to the number in the United States. (It is however likely that the number of graduate students enrolled in

Ph.D. study of superconductivity in Japan is significantly lower than in the U.S., perhaps by a factor of 2, see §2.2). Whereas the greatest concentration of researchers in Japan is in private industry, the United States has a relatively larger concentration of researchers in their national laboratories.

Our JTEC Panel was much impressed by the important role that the Japanese government played in setting the overall policy and priorities for the Japanese R&D program, and in guiding and monitoring the implementation of the R&D program, subsequently. Superconductivity R&D policy has often been implemented through long term 5 to 10 year national projects, many involving industry in a major way, and supported by both industrial and governmental funding. To encourage industry to follow government policy, appropriate incentives and resources are provided and long term commitments are made.

Funding for the Japanese superconductivity program stems from four sources: the Ministry of Education (MoE or Monbusho), the Science and Technology Administration (STA), the Ministry of International Trade and Industry (MITI), and the Japanese Railways (JR). Though strong competition exists between these agencies, significant cooperation, organization, and long range planning exist for the programs within each of the agencies. For example, coordination, cooperation, collaborations and healthy competition among university researchers have been fostered by the creation of the MoE Special Project for Research on High Temperature Oxide Superconductors [1], now headed by Professor Yoshio Muto of Tohoku University, with participants from the University of Tokyo, the Institute of Solid State Physics (University of Tokyo), the Institute for Molecular Science (Okazaki), the Institute for Materials Research (Tohoku University) and several smaller efforts at other Universities (Tokai, Osaka, and Hiroshima) (see Table 1.2 for the membership of this program in 1987). Within each of the academic institutions, cooperation and collaboration between the experimental groups is very strong. Furthermore, the coupling between the experimental and theoretical researchers has been strengthened as the quality of the experimental programs has improved. The rapid buildup of the high- T_c superconductivity program in Japan started early in 1987, soon after the validation of the Bednorz-Müller result by the University of Tokyo group [2]. It is fair to say that both in Japan and in the U.S. the research community responded very enthusiastically to the challenge of the new high T_c superconductivity phenomena.

1.3 Basic Research

In basic research, the greatest strength of the present Japanese effort is in academia, with some strong pockets of strength in their national laboratories

Table 1.2: Members of the Ministry of Education (Monbusho) Special Project on Research on High Temperature Oxide Superconductors (1987).

Member	Institution
Sadao Nakajima [†]	<i>Department of Physics, Tokai University</i>
Shoji Tanaka	<i>Department of Applied Physics, University of Tokyo</i>
Kazuo Fueki	<i>Department of Industrial Chemistry, University of Tokyo</i>
Hiroo Inokuchi	<i>Institute for Molecular Science</i>
Yasuo Endoh	<i>Department of Physics, Tohoku University</i>
Hidetoshi Fukuyama	<i>Institute for Solid State Physics, University of Tokyo</i>
Yoshio Muto [‡]	<i>Institute for Materials Research, Tohoku University</i>
Koichi Kitazawa	<i>Department of Industrial Chemistry, University of Tokyo</i>
Humihiko Takei	<i>Institute for Solid State Physics, University of Tokyo</i>
Masayasu Ishikawa	<i>Institute for Solid State Physics, University of Tokyo</i>
Seiichi Kagoshima	<i>Department of Pure and Applied Sciences, University of Tokyo</i>
Shinobu Hikami	<i>Department of Pure and Applied Sciences, University of Tokyo</i>
Kunisuke Asayama	<i>Faculty of Engineering Science, Osaka University</i>
Toshiizo Fujita	<i>Department of Physics, Hiroshima University</i>
Masatoshi Sato	<i>Institute for Molecular Science</i>

[†]Chairman (1987)

[‡]Present Chairman

and industry. Overall, it was the opinion of the JTEC Panel that the Japanese basic experimental research program is at a par with that in the U.S., but that their theoretical program is less vigorous. Some of the highlights of their basic research program (see Chapters 2 and 3) include the verification and significant amplification of the initial discovery of Bednorz and Müller [3] of superconductivity with $T_c \approx 30\text{K}$ in $\text{La}_{2-x}\text{Ba}_x\text{CuO}_{4-y}$ (see §3.5.1), detailed studies of the anisotropy of the transport properties of the oxide superconductors [4,5,6] (see §2.6.2), the first critical field studies of $H_{c2}(T)$ down to $T \rightarrow 0$ [7] made possible by the availability of megagauss fields (see §2.6.2), and detailed studies of electron-doped high- T_c superconductors [8] stemming from their initial discovery of these materials (see §3.5.5). It is interesting to observe that many of the Japanese pioneering achievements in basic research resulted from their notable achievements in materials research. Because of the Japanese strong emphasis on materials synthesis, it is likely that their contributions relative to the U.S. in basic research will increase in the near future.

In comparison with the U.S., Japanese universities are more weakly coupled to industry and to their national laboratories in basic research collaborations. Furthermore, the more general coupling between industrial, university and government laboratory basic research groups is significantly weaker than in the U.S. The Japanese are quite aware of these differences and are taking active steps to increase the coupling between these sectors and to strengthen their infrastructure in basic research generally. The MoE Special Project for Research on High Temperature Oxide Superconductors described above, and the ISTEK Program and ERATO Programs, described below, are all efforts that will enhance such coupling.

With regard to the quality of personnel involved in superconductivity R&D, the fraction of researchers with Ph.D. degrees is significantly below that in the U.S., especially in industrial R&D. This puts Japanese researchers at some disadvantage with regard to moving into new fields rapidly at a high level of creativity. Japanese industry provides excellent incentives for continuing education, as is also done by many U.S. companies.

Japanese companies also provide opportunities to earn Ph.D. degrees by carrying out basic research studies at the company through the so-called "paper doctor" program, which has many attractive features because the Japanese industrial laboratories are so much better equipped than are the university campuses. On the other hand, the JTEC Panel found this approach to lead to less broadly trained researchers than those graduating from major U.S. research universities. The JTEC Panel was very favorably impressed by the willingness of Japanese industry to hire talented individuals, without reference to the extent of their prior experience in their first R&D assignment. Interestingly, the top researchers in the various laboratories visited by the JTEC

team were already known to us and many had spent significant time in the U.S. early in their careers. We were frequently told that the Japanese believe that a broad exposure in a leading foreign research institution is an important step in the professional development of their top R&D personnel. In recent years, the leading research laboratories in Japan have started to promote personnel exchanges with foreign countries, especially the U.S. The number of such exchanges, however, is still quite small.

Just as the percentage of foreign graduate students in science and engineering is increasing in the U.S., our JTEC Panel heard of similar problems in Japanese universities, except that after the Ph.D. degrees were completed, their foreign students typically returned to their country of origin, unlike the case in the U.S. Many of the personnel in Japanese industrial R&D are at the B.S. or M.S. level of formal training, and are very willing to do sustained, systematic work, often involving highly directed teams. Such organized effort is valuable for certain types of superconductivity materials research, and the Japanese seem to excel in these areas. The Japanese superconductivity industry also benefits from a relatively well educated and well-motivated support staff, working in jobs not requiring advanced degrees.

Another factor relevant to comparing the research capabilities of the two countries lies in the availability of state-of-the-art research equipment, sophisticated materials characterization equipment and special materials research facilities. Whereas the U.S. was once very well positioned in these areas, the equipment and facilities capabilities for superconductivity research in Japanese universities are rapidly improving and in some cases are catching up to their U.S. counterparts. The equipment and facilities available in Japanese national and industrial laboratories engaged in superconductivity research have been rapidly improving and were judged by the JTEC Panel to be comparable to their counterparts in the best U.S. laboratories. The excellent research opportunities in Japan are starting to attract foreign talent, despite the large social and language barriers. The shutdown of the neutron scattering facilities at Brookhaven and Oak Ridge and the absence of a world class megagauss magnetic field facility in the United States are preventing U.S. researchers from competing effectively in important areas of superconductivity research.

1.4 Materials Research

The JTEC team was especially impressed by the materials research achievements of the Japanese laboratories. The Japanese believe that the key to research and eventual commercialization lies in the progress of their materials R&D, and are translating this philosophy into a sustained, systematic approach

Table 1.3: Characteristics of Japanese companies active in superconductivity research (1988).

Company	Sales	Net Income	Income (%sales)	R&D	R&D (%sales)	Growth (%/year)	Capital Expenditures
Fujitsu	\$13.7 B	\$256 M	1.87%	\$1.47 B	10.76%	8.53%	\$2.76 B
Furukawa	\$4.0 B	\$52 M	1.3%	\$0.092 B	2.3%	7.89%	\$0.61 B
Hitachi	\$24.5 B	\$700 M	2.9%	\$2.20 B	9.0%	4.0%	\$6.76 B
Matsushita	\$38.6 B	\$1302 M	3.37%	\$2.17 B	5.62%	5.07%	\$1.4 B
Mitsubishi Electric	\$18.9 B	\$178 M	0.94%	\$0.82 B	4.3%	5.9%	\$1.75 B
NEC	\$21.9 B	\$204 M	0.93%	\$3.46 B	16%	7.0%	\$2.0 B
NTT	\$45.3 B	\$1944 M	4.29%	\$1.45 B	3.21%	5.18%	\$5.42 B
Samitomo Electric	\$4.40 B	\$100 M	2.27%	\$0.18 B	4.05%	4.84%	\$1.91 B
Toshiba	\$28.6 B	\$486 M	1.7%	\$1.74 B	6.1%	7.7%	\$1.70 B

to materials synthesis and processing. Although few of the industrial laboratories we visited (Table 1.1) had world class basic physics research programs, almost all had sophisticated programs in materials research, including research on new materials, with special emphasis on achieving high critical current densities J_c in the high- T_c oxides. Materials research was especially strong in the industrial laboratories, many doing similar work and leading to a national duplication of effort. We found essentially no collaboration but rather intense competition between workers in one industrial laboratory with those in other industrial laboratories. This intense competition was in sharp contrast with the strong teamwork existing within a given institution.

All told, we visited 11 industrial research laboratories associated with 9 different companies. These laboratories were selected for their superior accomplishments in conventional or high T_c superconductivity (see Table 1.1). To look for possible correlations between achievements in superconductivity R&D and commercialization, we constructed Table 1.3. Characteristic of these Japanese companies who are successful in superconductivity research is a significant investment in R&D (weighted average of 6.8% of sales) and a high rate of capital expenditures (weighted average of 12.2% of sales).

Some of the most noteworthy Japanese achievements in materials research are highlighted in Chapter 3 in this report. Members of the JTEC team were captivated by the extraordinary achievements of the Japanese in the synthesis of single crystals of all the important classes of oxide superconductors, with regard to the size of the crystals, their quality, and the number of laboratories that had independently prepared large single crystals. Surprisingly, some of the best single crystals were grown at smaller universities such as Aoyama Gakuin and Yamanashi Universities [9,10]. With regard to the discovery of important

new oxide superconductors, the Japanese were contributing in a significant way, with the first observation (at NRI) of superconductivity with $T_c \sim 110\text{K}$ in the Bi-Sr-Ca-Cu-O system [11] and the first observation (at the U. of Tokyo) of an electron-doped high- T_c superconductor [8]. The JTEC team was very much impressed by the sustained, highly systematic studies at many industrial and national laboratories of the phase diagrams of synthesis parameter space for many of the oxide superconductors. These painstaking efforts were paying off in the synthesis of superior materials and the isolation of selected high- T_c phases. The more hierarchical "top-down" management, the longer term horizons and the different reward structures of Japanese industry, all provide a supportive environment for systematic materials R&D, although perhaps a less supportive environment for truly innovative research. Another area where the Japanese laboratories were in a leadership position relative to the United States was in the synthesis of materials with multiple sequential CuO_2 layers; several Japanese laboratories had prepared materials with 6 such CuO_2 layers and one laboratory showed us results for 7 layers. Increasing the number of CuO_2 layers per unit cell was once thought to be a method for increasing T_c , though detailed studies later showed that the maximum T_c 's were obtained with three to four CuO_2 layers per unit cell [12]. A tabulation of the major achievements in superconducting materials research by the JTEC Panel indicated approximate equality between the U.S. and Japan, with the Japanese leading in sustained, systematic effort and the U.S. program leading in innovation, but with less follow through. Our JTEC Panel was impressed by the appreciation given by both managers and peers to people who do synthesis, processing and scale-up.

Special reference should be made to the strength and breadth of approach of the Japanese laboratories in the synthesis of new superconducting materials. Consistent with the high priority given to materials research and the search for new materials, almost every Japanese laboratory that we visited had some effort in discovering new superconducting materials. Particularly notable is the very large program (over 100 researchers nationwide) in organic superconductors found in Japanese universities and in some national and industrial laboratories. This effort is an order of magnitude larger than the corresponding effort in the U.S. Though the highest T_c value for organic superconductors is presently only $\sim 11\text{K}$, there is great optimism among workers in this area for increasing T_c well above the present values. Working in a field that was originally pioneered in the U.S. and France, the Japanese researchers have discovered many new organic superconductors, and hold the record for the highest T_c ($\sim 13\text{K}$ reported by one laboratory on one occasion). With regard to heavy Fermion superconductors which are of great theoretical interest, there is presently much less activity (less than 15 researchers) in Japan relative to the U.S.

1.5 Special Initiatives

Traditionally, Japanese industrial laboratories have not been strongly involved in basic research, and this is also the case with regard to superconductivity research. To significantly increase the involvement of Japanese industry in basic research and to enhance technology transfer to industry, the concept of ISTECC (International Superconductivity Technology Center) was introduced by MITI early in 1988 and the concept was implemented into a brand new laboratory within 8 months, with Professor Shoji Tanaka, a famous professor of Applied Physics, retired from the University of Tokyo, as Director of Research. The speed of implementing a concept, preparing and approving a proposal, and funding, designing and constructing a facility was truly impressive. The major functions of ISTECC include a large research program (with laboratories in Tokyo and Nagoya), the sponsorship of one large symposium per year [13], the publication of a superconducting journal (4 issues/year) [14] with Japanese and English editions, the sponsorship of several small workshops (~ 170 participants) during the year, and the sponsorship of surveys and studies. The superconductivity research program at ISTECC is organized into six operating divisions: (1) Physics and Characterization, (2) Ceramic Materials, (3) Organic Superconductors, (4) Chemical Processing, (5) Physical Processing, (6) High Current Density Studies (Nagoya Division). There is also a computer services group that will provide various services to the whole laboratory. At the time of our visit, there were 86 researchers in Tokyo and 9 at Nagoya, 111 supporting industrial members (including 7 foreign companies, 5 of which were American), and 46 full support level companies. To qualify for full support level status, a company is required to contribute an entry fee of \$800K in addition to a sustaining fee of \$100 K/year and the salary support of up to two key researchers from their company. With \$6.8 M/year in direct support from MITI, ISTECC has a research support budget of \$17 M/year plus salary support. The ISTECC laboratory is located in rented space, consistent with the planned lifetime of 10 years for the laboratory.

Our JTECC Panel found the attitudes of Japanese companies toward ISTECC very interesting. Although the companies supporting ISTECC represent approximately one half of the Japanese Gross National Product, most company managers did not see much direct benefit of the consortium to their company needs and interests. Some managers even questioned the wisdom of committing so many resources for such a long time. By and large, the Japanese companies we visited feel that they can carry out whatever R&D is necessary for both their short term and long term needs. To them, participation in ISTECC is a "tax" for some overall benefit to the world. Whereas most of the ISTECC researchers are company employees whose careers will likely be enhanced by their ISTECC

experience, the ISTEK middle managers seem to face a less well-defined career path. On the basis of our laboratory visits, the JTEC Panel was strongly persuaded that ISTEK will have a significant impact on superconductivity research over the next decade.

The Japanese have been very quick to implement the consortium concept for superconductivity R&D through the MITI-sponsored ISTEK program, the STA-sponsored Multi-Core project, and the Monbusho-sponsored Special Project for Research on High Temperature Oxide Superconductors. The Japanese had previously used consortia in other fields through government leadership, though perhaps on a smaller scale. While the U.S. has also taken initiatives to form consortia, pilot centers, and Science and Technology Centers for superconductivity R&D, these consortia are not as fully implemented as are their counterparts in Japan. In most cases, the Japanese take time to reach a consensus, but once a consensus is reached, the Japanese government is prepared to assume a consistent, long-term commitment and to provide incremental resources for industrial participation. As our JTEC Panel reviewed the present Japanese industrial base in superconductivity, they concluded that their consistent, long-term (5-10 years) commitment to specific programs has allowed the Japanese superconductivity industry to leap frog the American counterpart.

The ERATO program is another attempt to enhance creativity of Japanese researchers. According to this program, scientists and technologists are considered as creative artists. The program identifies a handful of creative leaders each year, and allows each leader to designate a suitable R&D area for intensive exploration for a 5 year term. Each leader is given a budget of about \$3 M/yr (and often more) and is allowed to select 10-15 researchers to work with him. The only superconductivity program that has been selected thus far (out of the 14 programs in progress and the 7 completed programs) is that of Professor Goto of the University of Tokyo. The program, to be supported by STA from 1986-1991 is entitled "Quantum Magneto Flux Logic Project" and is based on the idea of using single flux quanta as bits of information. In this project, Professor Goto will explore circuits and applications of the d.c. flux parametron, a novel concept introduced by Goto and used here in the context of Josephson junction elements in a magnetic flux loop. Involved in the project is a team of 17 researchers from three companies working under the direction of Professor Goto of the University of Tokyo, making use of the different talents, technology and facilities of the participating organizations, and managed by a technical manager, on leave from Hitachi. No specific ERATO high T_c superconductivity projects are planned, because of the feeling that this research area is well covered by other funding mechanisms. On the other hand, some of the other ERATO programs may also have some small superconductivity projects.

though superconductivity is not their main focus.

1.6 Large Scale Applications

Our JTEC study has focused on both the science and the technology of superconductivity R&D in Japan. To discuss the topic of superconductivity technology and the potential for applications, it is useful to note the apparent difference of objectives of high T_c superconductivity R&D in Japan and in the U.S. Whereas the Japanese are heavily involved with large scale applications, such as magnetically levitated (Maglev) transportation systems, energy generation (Super GM) for the civilian sector, the U.S. emphasis is significantly directed toward defense goals, utilizing superconducting electronics, including microwave electronics, and compact energy storage systems (for SDI). Both countries have invested significantly in the application of superconductivity to high energy physics, although the bigger effort is in the U.S. via the Tevatron at Fermilab and the Superconducting Supercollider. It is noteworthy that even before the discovery of high T_c superconductivity, the Japanese were already committed to the long term conversion of their power generating stations to superconducting stator and rotor windings to reduce power losses (their Moonlight Project). Because of the large investment involved in this conversion, exploration of possible advantages of high T_c superconductors is of potential economic significance to the Japanese power industry.

Since both Japan and the U.S. have a significant superconductivity industry in place based on large scale applications, the JTEC panel believes that the present structure of this industry in each country will influence its future development as well as the likely role that the high T_c superconductors will eventually play. Therefore it is of importance to summarize some of the characteristics of this industry.

Both Japan and the U.S. have achieved a high level of industrial competence in high current, high field superconducting magnet technology, which is the cornerstone of this industry. In Japan, magnets and systems are supplied primarily by three major heavy electrical machinery companies: Hitachi, Mitsubishi and Toshiba. In the United States, magnets and systems are supplied by large companies such as General Dynamics, General Electric and Westinghouse. However, unlike the situation in Japan there is also major participation in magnet production by smaller companies such as General Atomics, Oxford Superconductors, Intermagnetics General (IGC), and American Magnetics. In Japan, superconducting wire and cables for magnets are supplied in part by cable and wire subsidiaries of Hitachi, Mitsubishi, and Toshiba. However, smaller, independent cable and wire companies such as Sumitomo Electric, Furukawa

Electric, Fujikura Electric, and Kobe Steel also provide aggressive competition in the materials market; in some cases these materials companies also supply magnets or magnet systems. In the U.S., superconducting wire and cable are mainly supplied by very small to medium-sized companies such as Intermagnetics General, Oxford, Supercon, Wah-Chang Teledyne and New England Electric (Cabling). Whereas U.S. superconducting wire and cable manufacturers supply the domestic market primarily, Japanese suppliers compete aggressively in the U.S. market.

At present, the only serious commercial market for superconducting magnets is the magnetic resonance imaging (MRI) market. About 1,000 systems have been installed in the U.S., with magnets mainly from G.E., IGC and Oxford (United Kingdom). About 200 systems are in operation in Japan, mainly from Hitachi, Mitsubishi, and Toshiba.

Several of the superconductivity companies and national laboratories we visited were actively considering the commercial possibilities of a "table-top" synchrotron orbital radiation (SOR) machine for lithographic applications by the semiconductor industry in the submicron range. At least one successful machine has already been built for NTT by Hitachi, but at so high a cost (over \$100 M), that these machines may not be commercially viable. The level of activity in the U.S. on the development of an SOR machine seems to be much lower than in Japan.

The principal stimulus for high field superconducting magnet development has traditionally come from advanced technology in other fields such as fusion, high energy physics, magnetic levitation, energy storage, power generation, etc. In both Japan and the U.S., these technologies are mainly sponsored and supported by government agencies and/or government (national) laboratories.

From our visits to various Japanese national laboratories (see Appendix B), our JTEC team determined that the Japanese government played a leadership role in developing and implementing a consistent policy toward the superconductivity industry. One of their policies is to contract out all superconducting magnet engineering to private industry, while maintaining a close working relation between a national laboratory and industry through the various phases of magnet design and development. This policy has been successful in enhancing the commercial capability of the Japanese superconductivity industry, and has provided a very effective vehicle for technology transfer. While both American and Japanese industrial leaders agree that technology transfer between national laboratories and industry is very difficult, the Japanese have managed to provide a significant number of successful examples of such technology transfers to the superconductivity industries (both in the case of large scale applications and superconducting electronics).

In contrast, U.S. agency policy has been mixed. In some cases, private

industry has been used for the development of the magnet technology (e.g., DOD, and DOE fusion programs), while in other cases (Fermilab, the magneto-hydrodynamics (MHD) program), magnets were both designed and built at national laboratories. Even when magnets have been built in American industry, there has not been a strong working relation between the national laboratories and industry, starting from an early stage in the design. It is the opinion of our JTEC team that the more consistent and more continuous industrial involvement of the Japanese companies with superconductivity projects over the past two decades has served to strengthen the technology experience base of their major magnet and magnet wire suppliers relative to those in the U.S. Efforts are now underway through consortia and other means to enhance technology transfer from the U.S. national laboratories to industry. It is to be hoped that these efforts will also include a more consistent procurement policy designed to stimulate engineering development in private industry in the early phases of superconductivity projects.

Both in Japan and in the U.S., the superconductivity industry is mainly driven by large, government-sponsored projects, as mentioned above. The two major current Japanese projects are: magnetically levitated (Maglev) trains and superconducting electric power generators (Super GM). With regard to magnetic levitation, a high speed vehicle has carried passengers at 520 km/hr on a 7 km long track near Miyazaki (Kyushu Island). Although steady progress has been made, many engineering problems remain to be solved before a serious inter-city main line system based on magnetic levitation can be considered. Magnetic levitation research for transportation applications has not been vigorously pursued in the U.S., mainly due to emphasis on developing airline systems and passenger aircraft.

In the area of energy generation, MITI has launched a 10-year, \$100 million project to develop a superconducting generator at 200 MW, with Fuji, Hitachi, Mitsubishi, and Toshiba. The long term goal over the next 30 years is to develop superconducting systems for energy generation in Japan, independent of potential benefits from the use of high- T_c superconducting materials. Despite extensive U.S. pioneering research (at MIT, G.E., and Westinghouse) with superconducting generators, there is presently no superconducting generator R&D project in progress in the U.S. There are however serious developments in this area in W. Germany and the U.S.S.R., as well as in Japan. The absence of such a capability could greatly weaken the commercial position of U.S. power generator manufacturers after 2000 AD.

At present, the U.S. also has two major superconductivity projects, the super-conducting supercollider (SSC) and superconducting magnetic energy storage (SMES). The SSC magnets have been engineered in the national laboratories, again following the pattern discussed above. An "industrialization"

program, leading to private manufacture has begun recently. The estimated cost of the magnets is around one billion dollars. The Japanese government has been invited by DOE to "collaborate" on the SSC project. Any serious commitment of funding from Japan would probably result in a request for participation in magnet manufacture. In this connection, it is interesting to note that the Japanese superconductivity group at the High Energy Physics Laboratory at Tsukuba (KEK) had definite ideas on how to improve the manufacturability of the SSC magnets (see §4.6).

The U.S. SMES project is an SDI activity, oriented towards pulsed energy requirements for beam weapons. However, the device may also be useful for shaving peak power needs by electric utilities. The present work (involving 2 separate contractor groups) is focused on the conceptual design, and no SMES construction is in progress. Without some practical experience with such large coils (> 100 MW-hr), it is difficult to assess the technical or economic viability of the system at this time.

The heart of superconducting magnet technology is the superconducting wire used to build the magnets. Both in Japan and in the U.S., the R&D and commercialization of the magnets and the magnet wire often occur in different laboratories and in different companies. At present there appear to be at least 7 world class Japanese suppliers of low- T_c superconducting wire, tape and cable. This compares with 4 companies in the U.S., of which one, Oxford, is British owned. With regard to the superconducting wire most widely used today, based on the Nb-Ti alloy with filaments in the 6 to 20 μm range, Japan and the U.S. both appear to have competent domestic suppliers. Development work for the SSC has improved the critical current J_c at a field of 5T, and similar progress has been made in Japan.

Advanced conductor work in Japan has made noteworthy progress in the development of submicron filaments, designed to lower a.c. and dynamic losses. The Japanese now have Nb-Ti wire with 0.5 μm filaments in production and are carrying out research on filaments as small as 0.03 μm (see §4.8.1). The Japanese work seems more extensive than the American work in this area.

Another area of conductor development on which Japan has placed special emphasis is the development of high J_c conductors at fields above 15 tesla. In a team effort between industry and NRIM, advanced multi-filamentary conductors with the $(\text{Nb,Ti})_3\text{Sn}$ and Nb_3Al compositions have been developed to a practical level. Work is also in progress in Japan on Chevrel phase conductors. This is not, at present, a large market area, but it does place the Japanese in a good strategic position to advance the high field magnet art up to 20 tesla and possibly beyond. Our JTEC Panel concluded that Japanese capabilities in superconductivity for the next generation of magnets (above 15T) significantly exceeds capabilities in the U.S. and the gap is widening.

High magnetic field testing facilities in both the U.S. and Japan are used for basic research and for the testing of materials for superconductivity applications, such as for high field magnets. For magnetic fields in the 15-30 tesla range, provided by water-cooled, superconducting and hybrid magnets, the principal Japanese facility is presently at Tohoku University, Sendai. It is of interest to note that $\sim 2/3$ of the usage of the high field facility at Sendai is for superconductivity research. The JTEC team judged the Sendai facility to be roughly comparable to the facilities at the Francis Bitter National Magnet Laboratory (MIT). However, the U.S. facility appears to have a much larger "outside users" program than exists at Sendai. The Japanese are planning a new government high field facility for Tsukuba City to include a 40T hybrid and a stand-alone superconducting magnet facility with fields above 20T. The superior Japanese work on superconducting materials operating above 15T (already noted) puts them in a position to leap-frog the U.S. in this important high field region.

1.7 Materials Processing

The realization of large scale superconducting applications depend heavily upon advances in the processing of superconducting wires and tapes (see Chapter 5). Since the Japanese already had a strong ongoing program on the processing of conventional (i.e., low- T_c) superconducting wires and tapes, it was natural for them to give significant emphasis to this area of materials R&D as they mounted their high- T_c superconductivity materials program. The visit of our JTEC team to Japanese laboratories confirmed that their R&D effort in the materials processing of high- T_c superconducting wires, tapes and thick films is extremely strong, and that good progress is being made, although still far short of the goal of equivalence to low- T_c superconductor parameters (J_c , H_{c2}). Many of the U.S. laboratories are also attacking this problem, and it is not at present clear whether sufficiently high J_c and H_{c2} values can be reached, nor who will eventually succeed in solving this difficult problem (see Chapter 5). Though most of the Japanese effort has its locus in Japanese industry, important generic R&D is carried out in their national laboratories (ETL and NRIM). With regard to processing techniques, the Japanese have perhaps had their greatest success with the quench and melt growth (QMG) method, a technique first applied at AT&T Bell Laboratories and quickly taken up by the Japanese (see §5.4 and §5.5). In the hands of the Nippon Steel group, the QMG method has yielded critical current densities of $J_c > 10^4 \text{ A/cm}^2$ at 1T. Other approaches to the processing of superconducting tapes have also shown promise, including the silver sheath method [15] and the doctor-blade method [16]. Although

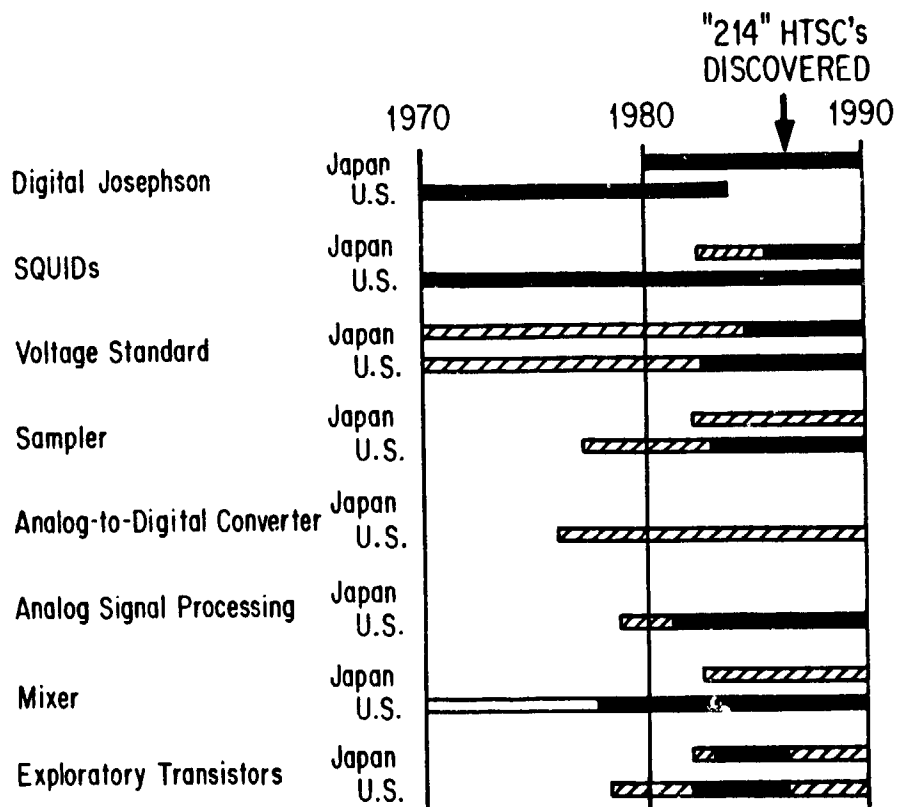


Figure 1.1: Comparison of Japanese and American R&D trends in low- T_c superconducting electronics. Schematic bar graph of the development of superconducting digital and analog electronics. The periods of most intense activity are indicated by the black regions of the bar, moderate activity is cross hatched and only small activity is unshaded.

Sumitomo Electric and other companies have stated that their goal for 1989 is a critical current of 10^5 A/cm^2 (at 77 K and zero field) in a high- T_c wire or tape, our JTEC Panel considers this goal as a major challenge to these Japanese researchers.

1.8 Superconducting Electronics and Thin Films

Although superconducting electronics presently plays only a small role in the commercial superconductivity industry, it is an area that the Japanese and Americans both consider to have high potential for future commercial applications. Both countries recognize that thin film processing is a very important technology for analog and digital superconducting electronics, and for the eventual utilization of both low- T_c and high- T_c superconductors. Therefore, both Japan and the U.S. are very actively engaged in R&D programs on thin film growth, characterization and application to superconducting electronics.

The pioneering research on superconducting electronics was done in the U.S. during the 1970's (see Fig. 1.1) with the IBM program in a leadership position. The Japanese only entered the field a decade later, but most Japanese companies (Fujitsu, Hitachi, NEC) remain committed to superconducting electronics,

after IBM and the other American companies dropped out in 1983 (though the largest single Japanese program at NTT was terminated at about the same time as the IBM program). These committed Japanese companies used relatively small groups (10–15 researchers), and focused their efforts on core technology issues such as integrated circuit (IC) processes and circuit design, rather than the extensive multichip package and systems work that IBM had pioneered. With the Japanese government setting the policy, and resources provided by MITI, ETL developed a generic improved all-refractory Josephson technology based on Nb/Al₂O₃/Nb trilayers. This technology was implemented in a ~10-level IC process by ETL, which was pervasively used by ETL, Fujitsu, Hitachi and NEC, and is now being adopted world-wide for analog applications. Because of their extensive experience with this refractory technology, these laboratories are well ahead of any U.S. laboratory, though the NIST voltage standard, the most sophisticated American effort, deserves special commendation (see §6.2.4).

The Japanese progress with superconducting circuits, particularly in logic circuits, has been great and is continuing effectively. The first microprocessor chip (4-bit) was produced by Fujitsu in 1986 and steady progress has since been made, achieving a 3056 gate chip operating at 1.1 GHz by 1989. While further progress with logic circuits is expected for the next year and beyond, the progress toward achieving dense memory chips has been slow and may limit long-term prospects for Josephson superconducting technology in computers. Presently MITI is sponsoring a 10-year high speed computer project, including Josephson technology, due to end in 1990, with a goal to achieve a high speed working system by the end of the program. The follow-on activity after the termination of the MITI project is uncertain, and will largely depend on the assessment by each of the three Japanese companies (Fujitsu, Hitachi and NEC) of the potential for significant commercialization of this digital technology.

With regard to analog superconducting applications, Fig. 1.1 shows that in almost all cases, the Japanese got off to a much slower start than the U.S. There is now good Japanese work in analog SQUIDs, and in some areas the Japanese may reach a leadership position (e.g., the Fujitsu digital readout for SQUIDs). The Japanese also have some superconductor-insulator-superconductor (SIS) mixer work and some Josephson voltage standard work (see Fig. 1.1), but little other high frequency electronics activity. In general, the U.S. has had more extensive experience in analog superconducting devices and is presently ahead in this area.

There are significant accomplishments in both Japan and the U.S. with regard to electronic device applications for high- T_c superconducting materials. At present, the Japanese effort is almost entirely directed towards materials research and they have less immediate concern with specific electronic device

applications. Thus, for the most part, the Japanese did not enunciate specific electronic device objectives for the near future, though they did indicate that passive elements (e.g., filters, interconnects, etc.) will probably be implemented before active devices (e.g., tunnel junctions). In the area of thin films, the Japanese had accomplished several notable achievements, including the first achievement of critical current densities $J_c > 10^6$ A/cm² at 77 K [17], the first growth of ultrathin ($\sim 100\text{\AA}$) high- T_c films [18], the first layer-by-layer growth of $n = 3, 4, 5$ layers of CuO₂ per unit cell in BiSrCaCuO films [12], and the first achievement of $J_c > 10^6$ A/cm² at 77K using a chemical vapor deposition (CVD) technique [19]. The thin film capabilities of Sumitomo Electric were especially impressive insofar as they had achieved J_c values in excess of 10^6 A/cm² at 77K in all three high- T_c systems (YBaCuO, BiSrCaCuO and TlBaCaCuO) during 1988 [17].

Another thin film achievement of note was accomplished through a Japanese-American collaboration [20] between NEC in Tokyo and Bellcore in New Jersey, whereby the NEC researchers provided a specially prepared silicon substrate with a double buffer layer of MgAl₂O₄/BaTiO₃ for lattice matching to the YBaCuO high- T_c superconductor which was deposited by Bellcore researchers using the laser ablation technique (see §6.3.2). Whereas inter-company collaborations would be very rare in Japan, this excellent research achievement provides one noteworthy example of industrial collaboration between two countries. Outstanding thin film growth is also being done at some Japanese universities, such as the University of Kyoto, Tohoku University, Osaka University, and is beginning at the University of Tokyo. Typically a Japanese industrial thin film group would consist of a strong leader (usually a Ph.D. who had spent some time abroad) and strong technical (B.S.-level) staff support to optimize the processing. To balance this relative strength of the Japanese program, is a less stimulating environment for the Ph.D. researcher with regard to active, critical peers to stimulate creative ideas. Our JTEC team also felt that in Japan the coupling between the thin-film materials researchers and the device experts was usually not as strong as in the U.S.

Our JTEC team judged that overall, the high- T_c superconducting thin film achievements in Japan and the U.S. are at present comparable and both are making very good progress. Direct comparisons were in some cases difficult to make because of different definitions of the superconducting transition (see discussion in §6.3). Broadly speaking, the U.S. has given greater emphasis to the laser ablation technique and is more vigorously pursuing the electron beam evaporation technology, while Japan seems to be emphasizing the sputter deposition and chemical vapor deposition technologies. Whereas the laser ablation and electron beam evaporation technologies are very valuable for research work, the Japanese may be in a stronger position with regard to practical applica-

tions since the sputter deposition and chemical vapor deposition techniques are more amenable for scale-up and device applications. In the U.S. at present, there appears to be more direct coupling of the materials to their potential device applications, probably reflecting the greater diversity and experience of U.S. researchers in low- T_c analog device applications. Since early high- T_c electronics applications will likely be in analog devices, the U.S. is at present well positioned to lead in these areas. U.S. leadership is threatened, however, if superior low- T_c technology remains the norm in Japan and if the analog device expertise in Japan grows in conjunction with their expanded superconducting thin-film and electronics developments. The Japanese are maintaining strong low- T_c electronics programs as a critical component of their superconducting technology development effort.

1.9 Concluding Comments

As the JTEC Panel members reflect on their visits to the Japanese laboratories certain themes have emerged. Because of their perceived importance of the superconductivity field, the Japanese have selected superconductivity as a flagship research area. The Japanese have indeed had a long record of interest in superconductivity, and in support of this interest the Japanese government has launched long-term sustained programs in superconductivity, both in large scale magnet projects starting in the 1970's, and in the 10 year MITI-sponsored digital superconducting electronics program of the 1980's, along with a long-term commitment of the Japanese Railway to the development of magnetic levitation technology. More recently in the high- T_c area, the Japanese government has been instrumental in launching the Ministry of Education Special Project on High Temperature Oxide Superconductors, the MITI-sponsored International Superconductivity Center (ISTEC), and the STA-sponsored Multi-core Project in Superconductivity. Much of the emphasis has been applications driven, where the importance of systematic, sustained effort has been appreciated and widely implemented. Recognizing the importance of materials research to both basic research and future commercialization, the Japanese have put relatively more effort into materials research than has the Americans, taking advantage of the Japanese strength in solid state chemistry, materials synthesis and materials processing.

As we talked to Japanese researchers we were surprised to discover the large number of similar challenges that we both face, including the difficulty of technology transfer from basic research at universities and applied research at government laboratories to industry, and the declining interest of native-born young people to pursue advanced graduate studies in science and engineering.

Through a comparative assessment of the Japanese and U.S. superconductivity R&D programs, the relative strengths and weaknesses of each program become more apparent, as do steps that should be taken to strengthen each program. A comparative R&D study could also lead to increased international cooperation in superconductivity R&D between Japan and the U.S. and an increased internationalization of the leading superconductivity R&D centers in Japan. The leading American R&D centers have for many years been highly international, benefiting from the talents of the most creative people around the world. This is one area where the Japanese can benefit from the positive U.S. experience. Since Japan and the U.S. are both strong in superconductivity R&D, there are many opportunities to work together and learn from each other. Because of the greater emphasis of the Japanese on sustained, systematic materials research, they are offering us strong competition in research and are developing the potential to pull ahead on commercial applications.

1.10 Acknowledgments

The JTEC Panel takes this opportunity to thank their Japanese hosts for the wonderful reception given to us, for the excellent arrangements they made for us, and for sharing so much information with us. The success of our study is largely due to their initiatives and to their cooperation. We owe special thanks to Dr. Nobuyuki Kambe of NTT, a former Ph.D. student of M.S. Dresselhaus at MIT, who provided invaluable logistic and technical support to our group while in Japan, thereby contributing very significantly to the success of this study. We also owe special thanks to Professor T. Enoki of the Chemistry Department in the Tokyo Institute of Technology who made a special trip to our hotel in Tokyo to give us an overview presentation on the Japanese program on organic superconductors. We thank him for his patience in answering many of our questions at that time and subsequently.

We would like to express our appreciation to Professor Y. Iye of the Institute of Solid State Physics (University of Tokyo), who kindly checked portions of this report and generously helped supply and check references. We also wish to thank the JTEC staff (Dr. George Gamota, Dr. Duane Shelton, Mr. Geoffrey Holdridge, Dr. Alan Engel) for their efforts and cooperation with all aspects of this JTEC study and to our sponsors (Dr. Frank Huband and Mr. Paul Herer) for their guidance. Ms. Cecilia Linnell, an MIT undergraduate, was exceptionally helpful in the preparation of the manuscript and deserves special commendation. We owe special thanks to Dr. Gene Dresselhaus of MIT for his technical contributions, critical comments, and for invaluable assistance with the preparation of the report. The Panel members individually are grateful

to colleagues and staff members at their home institutions who assisted in the preparation of the various chapters in this report.

Chapter 2

Superconductivity Basic Science

Paul M. Horn and Robert C. Dynes

2.1 Introduction

This chapter is an appraisal of the position of Japan in the area of basic studies on high- T_c superconductors. By basic research we refer to research aimed at elucidation of the fundamental mechanism of superconductivity in the high- T_c oxide superconductors. This Chapter is based on the result of visits to selected university, government and industrial laboratories in Japan. In addition to discussions on high- T_c oxide superconductors, there were limited discussions on other types of superconductors: conventional, organic and heavy fermion superconductors. In Table 2.1 are listed the institutions visited where sufficient basic research was being conducted to merit mention in our appraisal of the Japanese position.

This chapter is organized in the following fashion. In §2.2 we discuss our general conclusions from the visits and give an appraisal of general strengths

Table 2.1: Institutions visited with significant basic research.

University	Industry	Government Labs
Institute for Materials Research (Tohoku University)	Hitachi	ETL
ISSP (University of Tokyo)	NEC	NIRIM
U. of Tokyo	NTT (Ibaraki)	NRIM
	NTT (Musashino)	

and weaknesses of the Japanese basic research program. Here we discuss the relative contributions of industry, government laboratories and academia. Prior to our visit to Japan we prepared an appraisal of the U.S. position in basic research so that direct one-to-one comparisons could be made, and the presentation given here follows the format of our prior state-of-the-art appraisal. In some cases, after the visits and discussions in Japan, there was a change in the view of the Panel regarding the relative position of U.S. science. Because of the international character of research in this field, there were very few surprises and the JTEC visits generally resulted in an affirmation of our earlier opinions.

Basic research in this field of study necessarily must be intimately coupled with materials studies. The general comments in §2.2 of this chapter refer also to the materials studies and in most ways the separation of basic studies and materials research is artificial. Without sound materials studies, basic research is impossible and vice-versa. In order to compete in this field, an infrastructure of materials synthesis and diagnostics is necessary.

2.2 General Observations and Opinions

The basic research in Japan in high temperature superconductivity is performed in the three sectors: academia, industry and government laboratories, as is also the case in the U.S.

2.2.1 Universities

From visits to the universities listed in Table 2.1 (see also Appendix B), we conclude that the best basic research in Japan is of the highest international quality. Each of the institutes visited were addressing deep profound issues and competing well with their U.S. counterparts. From a poll of researchers at the various institutes, it is estimated that there are approximately 500 professional (Ph.D.) researchers in universities in Japan engaged in basic studies. This is a comparable number to that in the U.S. and the research output is also comparable. The detailed subfields are discussed in subsequent sections. Associated with these Ph.D. level researchers are approximately 200-300 students - a number we estimate to be fewer than that in the U.S. by a factor of two. This implies that on the long haul, more students will be trained in this field in the U.S. than in Japan and if superconductivity ultimately becomes a commercial technology, there exists a potential for more trained professionals in the U.S. The number and quality of the experimentalists in the U.S. and Japan are judged to be comparable.

The theoretical situation is a little different. While there are clearly identifi-

able leaders investigating the theoretical aspects of superconductivity in Japan, it appears that there are not the same numbers and "bench strength" that exist in the U.S. The theoretical physics community in the U.S. has focal points (e.g., the Institute for Theoretical Physics (ITP) in Santa Barbara, the Aspen workshops) where theories are continuously reviewed, critiqued, refined and rejected. In the judgment of the JTEC Panel, this type of regular extended review does not occur in Japan. The theorists in Japan are closely coupled to the experimental programs and they spend a good fraction of their time thinking about experimental results (usually from experimentalists in their own institution). These interactions between theorists and experimentalists significantly strengthen the Japanese basic research program on high- T_c superconductivity. Finally, it was observed that the leading Japanese theorists are comparable to leading theorists internationally, are well known in the U.S., and have often spent a significant fraction of their formative years in the U.S.

2.2.2 Industry

The largest single industrial laboratory that is engaged in fundamental research is NTT, both at their Ibaraki Laboratory and at Musashino. Several other industrial laboratories have pockets of good basic research but this research is often highly focused, reflecting the interest of the individuals involved. Nevertheless the work is very good and reflects a general feeling that a long term commitment to basic research is appropriate. Much of the best basic research work was found to be related to the excellence of their materials research programs. For example, a significant fraction of the most impressive single crystals of $(\text{La}_{1-x}\text{Sr}_x)_2\text{CuO}_4$ [10,21,22], $\text{YBa}_2\text{Cu}_3\text{O}_7$ [21,23,24,25], Tl-Ba-Ca-Cu-O , Bi-Sr-Ca-Cu-O [26] and the newly discovered electron superconductor $\text{Nd}_{2-x}\text{Ce}_x\text{CuO}_{4-y}$ [27] have been grown in Japanese industrial research laboratories [27,28,29,30,31]. Also, Japanese laboratories have excelled at the synthesis of new compounds, including the bismuth and thallium superconductors with over four CuO_2 layers per unit cell [12,32,33,34], and this success has not been matched in the U.S. The success of the Japanese workers in materials synthesis has afforded scientists from Japanese industry access noteworthy collaborations in to the world-wide community [10,22]. These successes in materials research attach great credibility to the basic research capabilities of these Japanese industrial laboratories.

The industrial laboratories, on the other hand, are not well coupled to Japanese universities. This was recognized by both parties, and several possible explanations were offered. Historically, universities have viewed industry as having a strong inclination towards applications-oriented R&D and these perspectives take time to change. An alternate explanation was offered by

a representative of a major industrial laboratory who suggested that serious barriers to university-industrial interactions were a result of competition between government agencies. It is our view that these interactions, however, are strengthening especially in superconductivity research, and if they ever reach the level of coupling that exists in the U.S. between universities and industry, both elements will benefit. The universities will have more ready access to the high technology offered by industry and the industries will have better access to the brightest minds.

2.2.3 Government Laboratories

In general the government laboratory programs were very much focused on the applied areas with emphasis given to practical goals. Compared to the national laboratories in the U.S., there was very little basic work going on in these Japanese laboratories, but in a few cases where there was some, it was quite respectable, if not outstanding quality. Most of the new materials work of the crystal chemistry variety was complemented by more focused materials science (for example microstructure studies) in support of practical applications.

The government laboratories were extremely well equipped by any standards. The highest quality instrumentation was available and used. The level of support in Japan seemed to be significantly better than comparable laboratories in the U.S. and if this instrumentation were easily accessible to university and industrial researchers, as is the case in the U.S., an enhanced national research efficiency would result. The various laboratories visited are apparently funded by different agencies and this seems to generate some competitive friction. Communication and collaboration between Japanese government laboratories could be improved to their mutual advantages. The situation is not unlike that in the U.S. where competition for funds among the national laboratories sometimes hinders collaboration.

Summarizing this section, there is excellence in basic science in all three sectors of research performers: universities, industry and government laboratories. For a variety of reasons the collaborations between these various units are not as strong as they are in the U.S., and as a result the quality and productivity of each of the units suffer to some extent. Nevertheless, Japan has had a good share of the major basic research accomplishments in the field of high- T_c superconductivity (some of which are listed in Table 2.2) and our visit gave ample evidence that this will continue. If strong interactions between universities, industry and government laboratories would occur, the Japanese could move solidly into a leadership position in high- T_c superconductivity.

In the following sections we summarize more specifically the more active areas of basic research.

Table 2.2: Major basic research accomplishments in high- T_c superconductivity from Japan

Accomplishment	Reference
Refined and legitimized original Bednorz and Müller result	[35]
High H_{c2} measurements	[7]
Discovery of Bi materials	[11]
Large and high quality single crystals	[27,36]
Electron doped superconductors	[8]
High critical current films	[17]
Bi and Tl compounds with over four CuO_2 layers per unit cell	[12,32,33,34,37]

2.3 New Materials

Materials research is an area which requires intimate coupling between chemists, physicists and materials scientists. This will be the main topic of Chapter 3 and therefore will not be discussed at any length here. However, in summarizing the major basic research achievements in Japan, we note that many are connected with major discoveries of new classes of superconductors as well as significant variations on known classes (see Table 2.2).

2.4 Theoretical Studies

There are strong pockets of theoretical activity mostly in the universities. The University of Tokyo has an especially strong group which addresses both the aspects associated with the basic mechanism responsible for superconductivity in the oxides and attempts to understand their unique physical properties such as tunneling, optical properties, transport, density of states determinations and electronic-band structure [38,39]. The theorists are well coupled to the experimentalists and function both in the role of consultation on new experiments and thinking through analyses of existing results. We estimate that there are about 100 professionals and 80 students actively doing theoretical studies on superconductivity. By comparison, in the U.S. the number is probably twice as large, with stronger communication between them.

Scientific progress on the theoretical origins of high temperature superconductivity remains slow both in Japan and in the U.S. Novel new theoretical ideas are being generated in both countries, but to date, there has been little agreement as to underlying mechanisms. Numerically intensive computations of the electronic structure of model oxide materials are at present dominated

by work in the U.S. [40]. However, it remains to be seen how important this work will ultimately be in sorting out the origin of electron pairing.

Finally, there has been a great deal of excellent theoretical work in both countries related to the eventual application of superconductivity [41]. This work includes studies of flux-flow and pinning (see §2.6.2), solid state properties including oxygen diffusion (see §3.4), and materials science properties including structural stability and materials compatibility.

2.5 Structural Properties

An important aspect of our understanding of this new class of superconductors is characterizing and understanding the structure of the materials. A large part of the feedback between the chemists and the physicists is via structural determinations and the relationship between structure and properties. Several different structural tools are used.

2.5.1 X-ray Crystallography

Routine structural determinations are performed in most research institutions. These are accomplished as a matter of course when materials are prepared and this usually involves routine powder structure analysis. A full structure determination (including atomic positions within the unit cell) usually requires high quality single crystal data taken on an automated four-circle diffractometer. However, even with these techniques, determination of the position of oxygen atoms is difficult and may require neutron scattering studies (see §2.5.3). Both Japan and the U.S. excel in various forms of detailed x-ray crystallography [42,43]. In selected sophisticated studies requiring high flux x-ray sources, the investigations in the U.S. are more extensive and detailed [43,44]. Straightforward access to good synchrotron sources has kept the U.S. in a firm leadership position in this field.

2.5.2 Electron Microscopy

High resolution transmission electron microscopy studies are used to look at both the crystallographic details of these oxides and phase transitions in them, as well as the properties of grain boundaries and the relationship between these microscopic details and the physical properties. Excellent detailed work is being performed both in Japan [45,46,47] and the U.S. [48] and the quality is comparable.

Research institutes and industrial laboratories in Japan are well equipped with high resolution microscopes (more so than in the United States, per-

haps because these instruments are almost all made in Japan) and they are being used effectively. We saw no studies addressing the details of the superconducting flux lattice which results when a magnetic field is applied to the superconductor and in this area the U.S. apparently dominates [49,50,51].

High resolution transmission electron microscopy (HRTEM), still something of a novelty in the U.S., is now almost routine in Japan. The JTEC team was repeatedly shown high resolution pictures of single crystal lattice fringes (see Fig. 2.1), grain boundaries, and defect structures. A typical example is shown in Fig. 2.1 where a high resolution image of the Tl-based compounds is shown [46]. We conclude that in this area the Japanese are better equipped and more active than their counterparts in the U.S.

2.5.3 Neutron Scattering

Neutron scattering has proven to be an especially valuable tool for basic structural studies [52,53,54,55,56]. This is for two reasons. Firstly, the oxygen scattering cross section for neutrons is relatively large and so the positions of the oxygen in the lattice can be located. As mentioned in §2.5.1, this information is especially difficult to extract from other techniques. Secondly, neutron scattering provides unique information about the magnetic spin structure and it is believed that the coupling between the carriers and the magnetic excitations is in some way intimately connected to the superconductivity (see §2.10).

2.5.4 Other Structural Tools

The scanning tunneling microscope (STM) can potentially be used to obtain atomic scale information about the physical and electronic structure of the surface of high temperature superconductors. For example, the STM could be used to obtain information on the carrier distribution on the various layers within the unit cell [57], or to characterize local structural defects that may be important to the functioning of these materials. In the electronic structure area, the STM could be used to map out the magnitude of the superconducting gap as a function of position within the unit cell. To date, the STM has not yielded definitive information with regard to the electronic structure but research continues in Europe, the U.S. and Japan. The U.S. appears to have a leading position in these studies.

Ion beam channeling has proven useful for study of both the amplitude of lattice vibrations and the degree of epitaxy achieved in thin films. This technique measures atomic displacements and crystal integrity very rapidly and is especially valuable for routine diagnostics [58,59,60]. At the moment, the U.S. is dominant in this area.

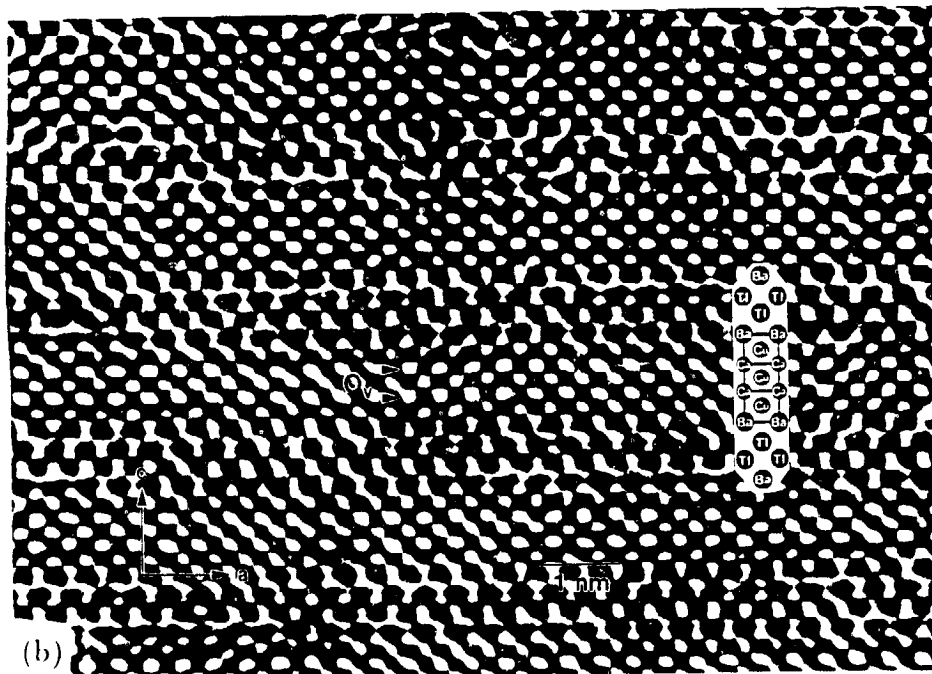
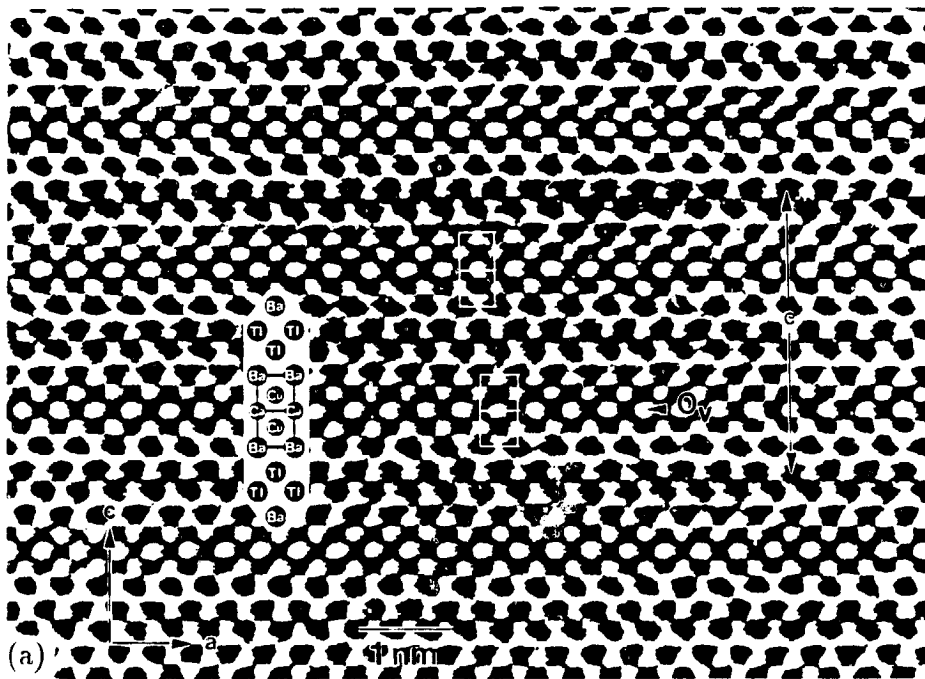


Figure 2.1: High resolution images taken on a 400 keV transmission electron microscope on two variations of the Tl_2 based high- T_c compounds [45,46]: (a) $Tl_2Ba_2CaCu_2O_8$ and (b) $Tl_2Ba_2Ca_2Cu_3O_{10}$. Photographs courtesy of Professor Hiraga.

2.6 Transport Properties

Transport studies have proven most valuable in both materials diagnostics and basic studies of the nature of the charge carriers. In addition, studies of the superconducting transition in applied magnetic fields have shown behavior which has been interpreted as due to flux creep. We divide our discussion of the transport studies into normal state and superconducting properties.

2.6.1 Normal State

Normal state studies can potentially provide unique information about high temperature superconductors. Specifically, they can help characterize the fundamental interactions in these materials, the band-structure, the electron-phonon and the electron-electron interaction strengths. Ultimately these parameters should provide information about the validity of Fermi-liquid theory. If Fermi-liquid theory is valid, these materials can be considered as ordinary metals with strongly attractive interactions between electrons. If Fermi-liquid theory is not valid, transport in these materials is uniquely new and different. The copper oxides are structurally anisotropic and this is mirrored in their transport properties. Both the resistivity and Hall effect show this anisotropy, which must be understood in any detailed theory for these materials.

With high quality single crystals available in Japan, high quality basic studies of the transport properties (electrical resistivity, Hall effect, magnetoresistance, thermopower, thermal conductivity) are being performed. While not leading the American effort, the Japanese studies of the transport properties in the normal state are of a level comparable to those in the U.S. and are closely coupled to theoretical investigations [6]. These studies will continue and we can expect important advances in this area from both Japan and the U.S. With a strong effort in single crystal growth and close coupling to theorists, this represents a notable area of strength of the Japanese program.

2.6.2 Superconducting State

Experiments on the superconducting state properties provide information about the symmetry of the superconducting state wavefunction, microscopic parameters including the coherence length and the field penetration depth and information regarding the strength of the coupling between the electrons and the excitation which leads to pairing. In addition, superconducting state studies provide us with important parameters (such as the critical current and critical fields) which are directly relevant to potential applications. Transport studies

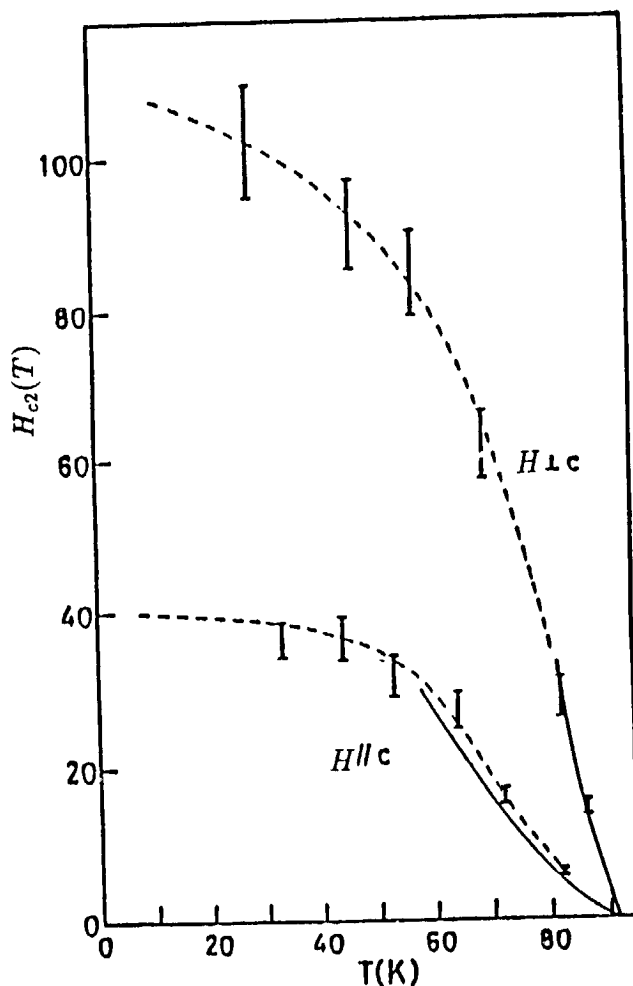


Figure 2.2: Pulsed field $H_{c2}(T)$ measurements of the ISSP group [7].

in the superconducting state can also be used to obtain information on the isotope effect [61,62].

The Japanese have been especially strong in studies of anisotropy issues and have done unique work at very high magnetic fields. Very high magnetic fields are necessary to explore the $H_{c2}(T)$ dependence, especially at low temperatures. Some very recent work by the ISSP group on the study of H_{c2} at very high fields [7] is shown in Fig. 2.2. The major point about this work is that it could only be done in Japan because of the unique megagauss magnetic fields facility at ISSP; such a high field facility is not available in the U.S.

At least four research groups in Japan are systematically studying the transport properties in the presence of high applied magnetic fields [5,24,36,63,64,65]. Earlier results in the U.S. which were interpreted as due to flux flow [66,67,68] have been questioned by some of these studies and the flux flow interpretation remains unclear. In this connection, some especially nice work by Iye et al. [69] have questioned these conclusions. Careful, systematic measurements in $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$ system by Suzuki and Hikita [70] show that resistive transition becoming sharper as the strontium concentration and the coherence lengths increase. This is illustrated in Fig. 2.3. Except for the unique Japanese work

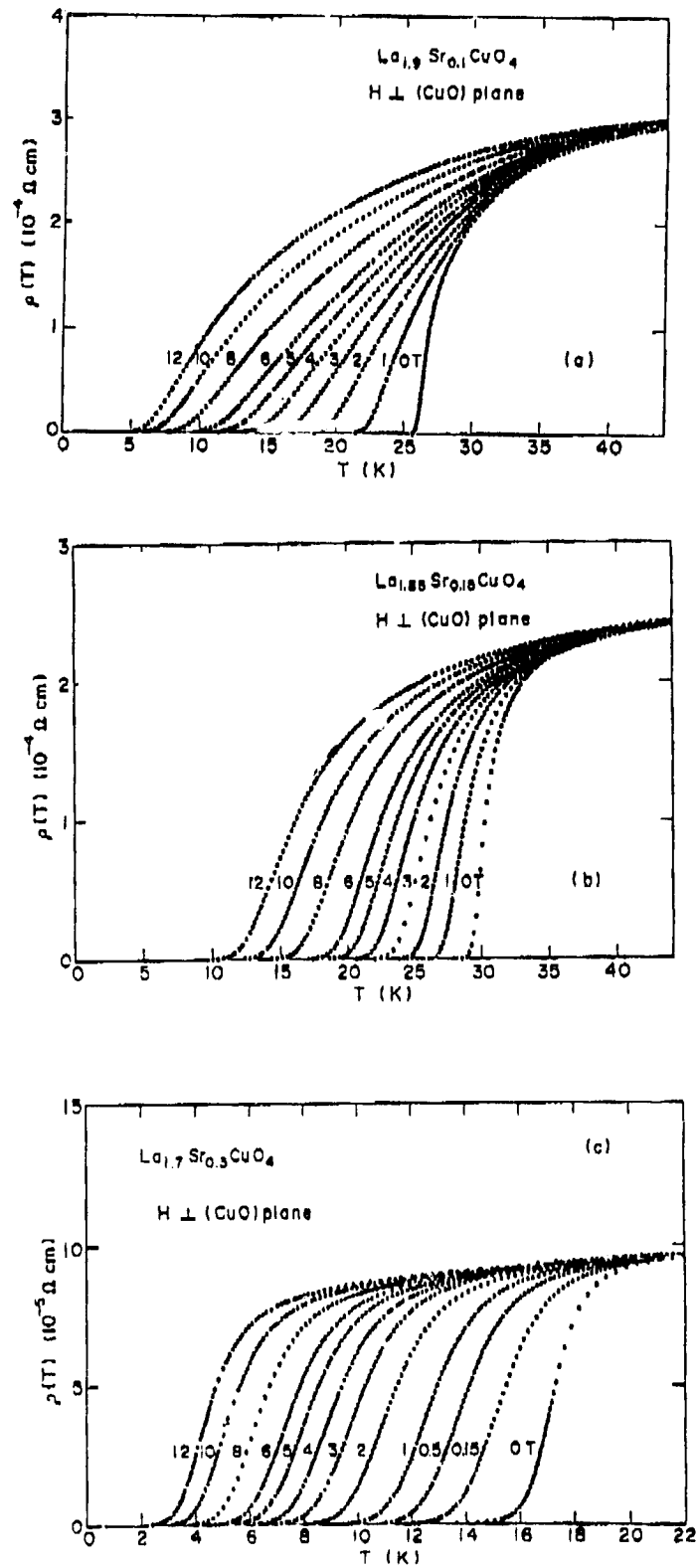


Figure 3: Resistive transitions in $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$ for different Sr concentrations. For increasing Sr, the magnetic field-induced broadening of the superconducting transition is reduced at high fields [65].

in the megagauss regime, the studies of transport phenomena in the superconducting state in the U.S. are at a comparable level with those in Japan and there is no clear leader in this area.

2.7 Thermodynamic Properties

Thermodynamic measurements such as heat capacity and magnetization are used both as routine diagnostics of materials and as probes to study the excitations from the superconducting ground state. For example, the temperature dependence of the specific heat at low temperatures can reveal the presence of low energy excitations [58,71,72,73,74,75]. Such studies require materials of high perfection because extrinsic disorder can be a source of low energy states. With the growth of high quality single crystals in Japan, the early leadership of the U.S. in this area is being challenged.

2.8 Optical Properties

Infrared reflectivity and absorption studies have been performed on several classes of materials (including the newly discovered electron doped copper oxides) in both the U.S. and Japan. These studies can be generally divided into two generic classes: high frequency measurements aimed at characterizing the normal state (e.g., the plasma frequency, ω_p , interband and intraband transitions, phonons, etc.) and low frequency, low temperature studies of the superconducting gap. In the former area, while some differences exist from one group to another, these studies generally show an absorption band [65] which has been interpreted as a highly correlated band in the band gap of the insulating compound. The energy scale for this band is at about 1000 cm^{-1} for $\text{YBa}_2\text{Cu}_3\text{O}_7$. While the interpretation is not yet accepted, it represents a novel idea brought about by a combination of careful optical studies on a set of materials prepared systematically. Optical studies at lower frequencies aimed at identifying the superconducting energy gap suffer from the same ambiguity as similar studies in the U.S. Nonetheless, excellent progress is being made and important insight is being gained. The success of much of the Japanese work follows from extensive studies relying on systematic materials synthesis [29,76,77]. The trends as a function of alloy concentration in various systems has produced an impressive compilation of data.

2.9 Electronic Structure Properties

Both theoretical (band structure calculations) and experimental (XPS, ARPES and positron annihilation) programs aimed at determining the electronic spectrum of these materials and correlating these results with the superconducting properties are going on both in Japan and the U.S. Band structure calculations on complicated materials are highly computation-intensive and thus require substantial computer time. The U.S. has a slight advantage here because of the ready availability of time on supercomputers.

The best experimental work on electronic structure usually requires highly sophisticated equipment. For example, angle resolved photoemission spectroscopy (ARPES) requires a highly intense beam of x-rays which can only be obtained with an electron storage ring or synchrotron. The best experimental work in this area has come from the U.S. and Europe where the synchrotron facilities are excellent. Some high quality work is also being done in Japan in this area [78,79,80,81].

2.10 Magnetic Properties

Bulk magnetic measurements, as mentioned in §2.7 from a thermodynamic standpoint are often used to provide routine diagnostics of new materials. Such magnetic measurements can, however, also be used to obtain information about microscopic interactions. For example, magnetic susceptibility data in the normal state can be used to obtain important Fermi-liquid parameters [82]. The trends of these parameters with doping provide important check points for theoretical electronic structure calculations. Excellent work is going on both in the U.S. and in Japan in this area.

Local magnetic properties are obtained in two generic ways: neutron scattering experiments and resonance experiments (e.g., EPR and NMR). Magnetic neutron scattering has proven very valuable in yielding detailed information regarding the coupling between the carriers and the magnetic excitations. The nicest work in this area has been a collaboration between American and Japanese investigators [54,83,84], and the work has greatly benefited from the large single crystals supplied by the Japanese [10,22]. However, at the moment, the only large research neutron reactor operating in the U.S. is at NIST in Gaithersburg, MD and unless alternatives are found, the leadership in the area of magnetic neutron scattering studies could go to Europe or Japan. With the highest quality large single crystals being grown in Japan and an available Japanese source of neutrons with people skilled in the technique [55], the U.S. program is in a precarious position. To date, the two pulsed spallation sources

in the U.S. (at Argonne and Los Alamos) have not filled the gap of the steady state sources.

Resonance experiments provide information both about local moments and about the conduction electron spins. High quality samples are essential to avoid effects from magnetic impurities. A particularly nice example of work in this area is the recent Japanese NMR experiment on single crystals of $\text{YBa}_2\text{Cu}_3\text{O}_7$ [85]. The temperature dependence of the ^{63}Cu [86] nuclear relaxation provides strong evidence that the superconducting ground state has a large gap for quasiparticle excitations [87,88]. The U.S. has traditionally had an extremely strong program in this area with excellent measurement tools. However, with the growth of high quality single crystals in Japan, the leadership of the U.S. in this area is being challenged. Muon spin resonance (μSR) has proven a valuable tool for studying local fields in high- T_c superconductors and has provided an important early measurement of the superconducting penetration depth. Because this technique is facilities-limited, the best work [89] has been done by a truly international collaboration at the Tri-university Meson Factory (TRIUMF) in Vancouver, Canada.

2.11 Concluding Comments

While the various techniques and investigations discussed in this chapter are not intended to be all-inclusive they do give a flavor for the basic research program in Japan. This program has a heavy emphasis on materials research, but indeed addresses fundamental questions. It is not expected that any one of these studies mentioned above will provide the unique breakthrough which will identify the pairing mechanism for superconductivity in the oxides. It is our belief rather that each of these sub-fields will contribute to the overall pool of knowledge. The effort in Japan is expanding in universities, industry and government laboratories to contribute to many aspects of that pool. It is still the case that the breadth and infrastructure in the U.S. leads the world in this research area. In the U.S. there is a network of scientists who have proven expertise in certain techniques and research areas, and these people are well known in the research community. Within this network the communication is strong, and collaborations naturally occur in all three sectors - universities, industry and government laboratories. While intellectually led by the universities, the basic research programs in some Japanese industrial and government laboratories are strong and growing. If the three elements (university, industry and government laboratories) improve their interactions so that genuine collaborations become common place, basic research in Japan in the area of high T_c superconductivity will be on a par with that in the U.S.

The "scientific infrastructure" in the U.S. continues to function well, but is slowly eroding, while in Japan it is growing. The Japanese believe that they can show the world that they can make significant contributions to basic research in this area, and thus superconductivity research in Japan has become something of a flagship in Japan, with commitments of research resources comparable to those in the U.S. With such a strong Japanese effort, significant science will result.

Chapter 3

Superconducting Materials

M. Brian Maple

3.1 Introduction

Materials underlie all basic research on superconductivity, as well as the technological applications of this phenomenon. Superconducting materials research involves the synthesis and characterization of new and known phases of superconducting materials in polycrystalline and single crystal bulk, thin film and composite form. It is a very broad and interdisciplinary research area which enjoys the participation of physicists, chemists, metallurgists, ceramists, and engineers. This Chapter is restricted to the major classes of nonconventional superconducting materials (oxide, organic, and heavy fermion superconductors) in polycrystalline and single crystal form; thin films and composites of conventional superconductors (e.g., Nb-Ti, NbN, Nb₃Sn) and high- T_c oxide superconductors are discussed in Chapter 4 on Large Scale Applications of Superconductivity, Chapter 5 on Processing of Superconducting Materials, and Chapter 6 on Superconducting Electronics and Thin Films, respectively.

3.2 Superconducting Materials Research Prior to 1986

Prior to the discovery of high T_c superconductivity (i.e., $T_c > 30$ K) in layered copper oxides in 1986, extensive research was underway on the following types of superconducting materials: conventional high T_c superconductors (e.g., A15's, NbN, ternary Chevrel phase compounds), magnetic superconductors (e.g., rare earth (R) compounds such as RRh₄B₄, RMo₆S₈, RMo₆Se₈), heavy fermion superconductors (e.g., CeCu₂Si₂, UBe₁₃, UPt₃, URu₂Si₂), and organic supercon-

ductors. In the U.S., a great deal of attention was devoted to ternary compounds and magnetic superconductors from the mid 1970's to the early 1980's, heavy fermion compounds from the late 1970's to 1986, and, to a lesser extent, organic compounds from the late 1970's to 1986, as well as the oxide superconductors (the precursors of the present high- T_c oxide superconductors) from the early 1970's to 1986. In 1986, much of the attention of U.S. researchers was on heavy fermion superconductors (because of the possibility that these compounds exhibit a type of anisotropic superconductivity, analogous to the triplet superfluidity of liquid ^3He , involving a magnetic pairing mechanism), while the Japanese were vigorously pursuing all types of superconductors including ternary compounds, R-based magnetic superconductors, oxides, organic compounds, and conventional high- T_c superconductors, in addition to heavy fermion compounds (mostly CeCu_2Si_2 , because of the radioactivity of U). However, at the beginning of 1987 virtually all research on these superconducting materials on a worldwide scale came to an abrupt halt and was redirected to high- T_c oxide compounds. Only recently have many researchers begun to drift back to these pre-1986 superconducting materials.

3.3 Superconducting Materials Research After 1986

In addition to the oxide superconductors, organic superconductors are attracting a great deal of attention in Japan (see §3.6), whereas heavy fermion superconductors are receiving increasing attention in the U.S., as noted in §3.7. To some extent, the excitement generated by research on the new high- T_c oxide superconductors during the past several years has focused attention on the phenomenon of superconductivity and its technological applications, resulting in renewed interest in the conventional high- T_c superconducting materials, particularly the A15 compounds.

3.3.1 Polycrystalline Materials

Most of the measurements on high- T_c oxide superconductors (and other superconducting materials, as well) have been made on polycrystalline specimens. Polycrystalline materials are generally quite suitable for studying the effect of chemical substitutions on T_c , searching for new superconducting phases, and the measurement of properties that are not affected by anisotropy (e.g., T_c , specific heat in zero magnetic field). However, for anisotropic properties (e.g., electrical resistivity, magnetization, H_{c2}) or properties that are sensitive to the "weak link" behavior of the intergranular regions in the sintered polycrys-

talline oxides (e.g., electrical resistivity in an applied magnetic field, or J_c), single crystal specimens are necessary. Nonetheless, a great deal of useful (and valid!) information can be obtained at a relatively rapid rate by working with polycrystalline specimens, particularly during the earlier stages of research on a new superconducting phase, although good judgment must always be exercised in assessing the validity of polycrystalline results. Polycrystalline specimens of the oxides are generally prepared by solid state reaction of metal oxides and carbonates. Other specialized techniques can be employed, such as sol-gel processing, which is also being examined as a method for producing fibers and films for technological applications (see Chapter 5).

3.3.2 Single Crystals – Anisotropy and Implications for High Critical Current Densities

Investigations on single crystals have allowed the anisotropy of the physical properties of the layered copper oxide high- T_c superconductors such as H_{c2} and J_c to be determined. Anisotropic properties of interest include the electrical resistivity, magnetoresistance, thermal conductivity, H_{c2} , J_c , etc. The anisotropic behavior of two of these properties H_{c2} , J_c , are of particular interest in connection with technological applications of the high- T_c ceramic materials. While the upper critical field H_{c2} is itself one of the fundamental superconducting parameters of technological importance, analysis of its temperature dependence yields an estimate of the superconducting coherence length, a quantity that is relevant to another fundamental technological parameter, the critical current density J_c . Specifically, the values of the initial slopes of H_{c2} at T_c indicate extremely small and anisotropic coherence lengths $\xi_a \approx 10 \text{ \AA}$ within the basal plane (within the conducting CuO_2 planes) and $\xi_c \sim 2 \text{ \AA}$ along the c -axis (perpendicular to the conducting CuO_2 planes). Such short coherence lengths are comparable to or smaller than the thickness of intergranular regions in polycrystalline materials. The intergranular regions may contain impurity phases, compositional variations, oxygen deficiencies, etc., which render the regions only weakly superconducting or even normal, so that they behave as weak links between superconducting grains, and, in turn, limit J_c . Fortunately, J_c has been found to be intrinsically high within the crystallites according to measurements on single crystal thin films (see §6.3.2) and bulk [90] specimens. The highest values of J_c that have been reported to date have been achieved on epitaxially grown single crystal thin films and are $\geq 5 \times 10^6 \text{ A/cm}^2$ (see §6.3.2).

Recently, there has been much interest in thermally activated flux motion in the high T_c oxide superconductors, both from the point of view of the basic physics underlying the phenomenon as well as its implications in limiting J_c in these materials [66,67,68]. Numerous investigations have been carried out

on a worldwide scale on the relaxation of the magnetization in superconductors subjected to magnetic fields [67,91,92], the temperature and magnetic field dependence of the resistive superconducting transition curves [66], the observation of the Abrikosov flux lattice by means of magnetic decoration, and the response of the Abrikosov lattice to forced oscillations [50,93]. Recent work in Japan and the U.S., in particular, on several types of high- T_c oxide materials has revealed that the broadening of the resistive superconducting transition curves in an applied magnetic field does not depend on the direction of the current with respect to the magnetic field, but rather depends on the orientation of the field with respect to the crystal axes. These observations have raised serious questions regarding the relevance of the Lorentz force driven flux creep model [94,95,96] and have elicited an alternative explanation involving superconducting fluctuations [96,97]. A considerable challenge to the science and technology of high- T_c superconducting ceramics is the development of ways of introducing defects into the materials that will be effective in pinning fluxoids, and, in turn, increasing J_c in high magnetic fields in the liquid nitrogen temperature range.

Even without the problems associated with the grain boundaries, the misalignment of the crystallites would significantly reduce J_c from its maximum value in the direction of the a - b plane. It has proven difficult to determine the anisotropy within the a - b plane for the orthorhombic materials like $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ due to the twinning encountered in most single crystals. High quality single crystals of the high- T_c oxide superconductors are essential for a detailed understanding of the basic physics of these materials, since single crystals allow the anisotropy of the physical properties to be investigated, eliminate complications associated with grain boundaries, etc.

Japanese researchers have been aggressively addressing these problems and have made important contributions to their solution as discussed below. The availability of high quality single crystals (for a number of high- T_c materials, beyond what is available in the U.S.) have put Japanese researchers in an advantageous position. In some cases, however, a stronger coupling between single crystal growers and researchers needing such special materials for important fundamental studies could have increased the effectiveness of the overall research output.

3.4 New Superconducting Phases

In addition to enhancing the quality and optimizing the physical properties of known superconducting phases, an especially important aspect of superconducting materials research is the search for new superconducting phases.

New superconducting phases provide information which can be used to relate the occurrence of superconductivity to materials parameters such as structure, atomic sizes, average valence electron concentration, etc. (empirical rules such as Matthias' rules for superconductivity of transition metals [98]), are a source of new phenomena, and may yield enhanced superconducting characteristics such as superconducting critical temperature T_c , upper critical field H_{c2} , and critical current density J_c , and mechanical properties that are suitable for technological applications. Virtually every industrial, national, and university laboratory visited by this JTEC Panel in Japan has a superconducting materials research program with some level of activity devoted to the search for new superconducting materials. In contrast, superconducting materials research is on the decline in the U.S. and only about ten U.S. laboratories are presently engaged in large scale searches for new superconducting compounds. Some of the contributions of Japanese researchers to the search for new superconducting phases are outlined in §3.5

The search for new superconducting materials has always been an empirical enterprise, and this is especially true for the new high T_c oxide materials. Many of the new high- T_c superconducting materials have been found by chemical substitution into a known superconducting phase, an approach that can result in

1. the optimization of superconducting parameters such as T_c , H_{c2} , and J_c of the known superconducting phase;
2. new examples of the known superconducting phase; and
3. entirely new superconducting phases.

An example of (1) is the increase of T_c from ~ 30 K to ~ 40 K by replacing Ba with Sr [99,100,2] in $\text{La}_{2-x}\text{Ba}_x\text{CuO}_{4-y}$, the material originally investigated for superconductivity by Bednorz and Müller [3]; examples of (2) are the discoveries of superconductivity in $\text{La}_{2-x}\text{M}_x\text{CuO}_{4-y}$ where M is the monovalent alkali metal Na [101,102] rather than a divalent alkaline earth (Ca, Sr, Ba) and in $\text{Ln}_{2-x}\text{M}_x\text{CuO}_{4-y}$ (Ln = Pr, Nd, Sm, Eu) where M is tetravalent Th [103] in place of tetravalent (or intermediate valent) Ce [8]; while examples of (3) are the discovery of the $T_c = 92$ K superconducting phase of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ by replacing La by Y [104] in $\text{La}_{2-x}\text{Ba}_x\text{CuO}_{4-y}$ and the discovery of superconductivity in $\text{Tl}_2\text{Ba}_2\text{Ca}_{n-1}\text{Cu}_n\text{O}_{2n+4}$ at 125 K for $n = 3$ [105] as a result of the substitution of Tl for rare earth R and Ca for Ba in the $T_c = 92$ K phase of $\text{RBa}_2\text{Cu}_3\text{O}_{7-\delta}$. Other routes to the discovery of new high- T_c superconducting phases are the testing for superconductivity of new phases reported in the literature, or the exploration of multicomponent phase diagrams in connection with superconductivity studies.

Table 3.1: Superconducting oxides known prior to 1986.

Compound	T_c	Discovery
TiO, NbO	~ 1 K	'64 - J. K. Hulm et al.[115]
SrTiO _{3-x}	~ 0.7 K	'64 - J. J. Schooley et al.[116]
A _x WO ₃	~ 7 K	'64 - Ch. J. Raub et al.[117]
A _x TO ₃ (T = Mo, Re)	~ 4 K	'69 - A. W. Sleight et al.[118]
Ag ₇ O ₈ X	~ 1 K	'66 - M. B. Robin et al.[119]
Li _{1+x} Ti _{2-x} O ₄	~ 14 K	'73 - D. C. Johnston et al.[120]
Ba(Pb _{1-x} Bi _x)O ₃	~ 14 K	'75 - A. W. Sleight et al.[121]

Numerous investigations have been made of the effect of oxygen concentration on the superconducting and magnetic properties of the high- T_c cuprate superconductors. For example, as the oxygen vacancy concentration δ is increased from 0 to 1 in the YBa₂Cu₃O_{7- δ} system, T_c decreases from ~ 92 K for $\delta \approx 0.1$ to ~ 60 K for $\delta \approx 0.3$ to ~ 0 for $\delta = 0.6$ [106,107]. For $\delta \geq 0.6$, the compound exhibits antiferromagnetic ordering of the Cu²⁺ magnetic moments which reaches ~ 500 K for $\delta = 1$ [108]. The Néel temperatures and shapes of the specific heat anomalies due to antiferromagnetic ordering of the R³⁺ magnetic moments are also strongly affected by changes in δ [109,110,111]. Superconductivity with $T_c \approx 40$ K can be induced in the La₂CuO_{4-y} parent compound by increasing the oxygen content above 4 ($y < 0$) [112,113] which actually leads to a new orthorhombic phase [114].

The search for new high- T_c superconductors has centered on oxide compounds following the breakthrough made by Bednorz and Müller in 1986. The oxide superconductors discovered prior to 1986 are listed in Table 3.1. It is of interest to note that these early discoveries took place in the U.S. and Europe. The Japanese entered the field in about 1976 through work initiated at the University of Tokyo. Because of the broad experience at the University of Tokyo in ceramics and superconductivity, a broadly based program in materials, characterization and properties measurements developed. This group was thus in an excellent position to make rapid progress in the new high- T_c oxide superconductors discovered in the La-Ba-Cu-O system by Bednorz and Müller [3]. The University of Tokyo group was quick to identify the phase responsible for the $T_c = 30$ K superconductivity as La_{2-x}Ba_xCuO_{4-y} with an orthorhombically distorted K₂NiF₄ structure and to demonstrate that the superconductivity was a bulk phenomenon [35]. Corresponding to Table 3.1, the new high- T_c oxide superconductors discovered since 1986 are listed in Table 3.2. Major discoveries have been made in France, Japan, Switzerland, and the United States.

Table 3.2: Superconducting oxides discovered after 1986

Compound	T_c	Discovery
$(La_{2-x}M_x)CuO_4$;		
M = Ba	~ 30 K	'86 J. G. Bednorz & K. A. Müller[3]
M = Sr	~ 40 K	'86 K. Kishio et al.[2]
	~ 40 K	'87 R. J. Cava et al.[99]
M = Ca	~ 20 K	'87 K. Kishio et al.[2]
YBa ₂ Cu ₃ O ₇	~ 95 K	'87 M. K. Wu et al.[104]
LnBa ₂ Cu ₃ O ₇	~ 95 K	'87 Various laboratories[122]
$(La_{2-x}Na_x)CuO_4$	~ 20 K	'87 J. T. Markert et al.[102]
Bi ₂ Sr ₂ CuO ₆	~ 22 K	'87 C. Michel et al.[123]
Bi ₂ Sr ₂ Ca _{n-1} Cu _n O _{2n+4}	~ 110 K	'88 H. Maeda et al.[11]
Tl ₂ Ba ₂ Ca _{n-1} Cu _n O _{2n+4}	~ 125 K	'88 Z. Z. Sheng & A. M. Herman[105]
$(Ba_{1-x}K_x)BiO_3$	~ 30 K	'88 R. J. Cava et al.[124]
Nd _{2-x+y} Ce _x Sr _y CuO ₄	~ 20 K	'89 J. Akimitsu et al.[125]
RBa ₂ Cu ₁₄ O ₈	~ 80 K	'88 D. E. Morris et al.[126]
Pb ₂ Sr ₂ (Ca, R)Cu ₃ O _{8+y}	~ 77 K	'88 R. J. Cava et al.[127]
$(Ln_{2-x}Ce_x)CuO_4$	~ 25 K	'89 Y. Tokura et al.[8]
$(Ln_{2-x}Th_x)CuO_4$	~ 20 K	'89 J. T. Markert & M. B. Maple[103]
Ln ₂ CuO _{4-x-y} F _x	~ 25 K	'89 A. C. W. P. James et al.[128]
Nd _{2-x+y} Ce _x Ba _y Cu ₃ O _{10-z}	~ 30 K	'89 H. Sawa et al.[129]
⋮		
?	$T_c > 300$ K?	(TIP OF THE ICEBERG?)

3.5 Japanese Research on high- T_c Oxide Superconductors

Japan has an intense and broadly based national research program on high- T_c superconducting oxides that involves industrial, national and university laboratories. At present, the program is predominantly experimental with a strong emphasis on materials, which seems appropriate in view of the fact that research on this complex and challenging problem is in an early phase. The Japanese clearly recognized the importance of materials research for enhancing their basic research program on the one hand, and the potential for eventual commercialization of products based on high- T_c superconductors, on the other hand. There are many industrial, national, and university laboratories with excellent programs in the synthesis of polycrystalline and single crystal bulk, thin film, and composite superconducting materials. Included in almost all of these research efforts is the search for new superconducting materials, an extremely important enterprise that appears to be more strongly emphasized in Japan than it is in American laboratories. Japanese researchers also seem to be more willing to carry out systematic investigations of multicomponent phase diagrams and complex processing methods in connection with the synthesis of superconducting materials than their U.S. counterparts. Although research and development of superconducting materials appears to be an important national objective in Japan, competition between individual research groups as well as industrial and university laboratories, in general, seems to be quite intense. A new component that augments the traditional triumvirate of industrial, national and university laboratories and illustrates the resolve of the Japanese national effort on high temperature superconductivity is the formation of ISTECC which has a primary laboratory in Tokyo and a subsidiary laboratory in Nagoya (see Chapter 1). Japanese materials research on high- T_c superconductivity has been very competitive on a worldwide scale. Some of the highlights of Japanese materials research on high- T_c oxide superconductors are summarized in this section.

3.5.1 $\text{La}_{2-x}\text{M}_x\text{CuO}_{4-y}$ ($\text{M} = \text{Ca}, \text{Sr}, \text{Ba}, \text{Na}$) Compounds

Evidence for superconductivity with an onset near 30 K was first reported by Bednorz and Müller in 1986 in the La-Ba-Cu-O system [3]. However, this work was initially regarded with a certain amount of skepticism due to the long history of reports of superconductivity at high temperatures (well above 23 K, the high T_c record held by the A15 compound Nb_3Ge since 1973) in materials such as CuCl , CdS_2 , etc., that were transient and/or irreproducible, or, in short, could not be experimentally verified. Japanese researchers at the University of

Tokyo provided the first convincing confirmation of the work of Bednorz and Müller [3], by preparing single phase materials with relatively sharp resistive superconducting transitions, demonstrating the Meissner effect, and determining the crystal structure [130]. In subsequent work, superconductivity was also found to occur at ~ 20 K in the $\text{La}_{2-x}\text{Ca}_x\text{CuO}_{4-y}$ system [2], and at ~ 40 K in the $\text{La}_{2-x}\text{Sr}_x\text{CuO}_{4-y}$ system [99,100,2]. Somewhat later, superconductivity was also discovered in the $\text{La}_{2-x}\text{Na}_x\text{CuO}_{4-y}$ system [101,102]. Although these materials have been supplanted by other oxides with yet higher critical temperatures as candidates for technological applications, the research on the lanthanum cuprate materials has yielded some of the basic characteristics of the high- T_c oxide superconductors (see Chapter 2). The substitution of divalent Ca, Sr, or Ba or monovalent Na for La in $\text{La}_2\text{CuO}_{4-y}$ dopes the CuO_2 planes with mobile holes. These holes destroy the antiferromagnetic ordering of the Cu^{2+} ions that occurs at a Néel temperature $T_N \approx 500$ K in the insulating phase and convert the material into a superconducting metal with a maximum T_c at $x \approx 0.15$ for alkaline earth solutes. Work on these materials proceeded at a feverish pace during 1987, and Japanese researchers have made many important contributions to the characterization of the magnetic and superconducting properties of the oxide superconductors by means of transport, magnetic, and thermal measurements, neutron scattering [54], etc., in addition to having independently discovered [2] superconductivity in Ca and Sr-doped $\text{La}_2\text{CuO}_{4-y}$. The highest quality single crystals that were used in the neutron scattering experiments carried out at Brookhaven National Laboratory in the U.S. were made in Japan where there are several excellent programs [27,29,30] for growing single crystal specimens of high- T_c superconducting materials, yielding crystals of some high- T_c materials that are superior to those available in the U.S.

3.5.2 $\text{RBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (R = Rare Earth) Compounds

Following the discovery in the U.S. by Wu et al. [104] of superconductivity near 92 K in the compound $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$, various laboratories in Japan and the U.S. independently and nearly simultaneously reported superconductivity near 92 K in the lanthanide (Ln) analogues $\text{LnBa}_2\text{Cu}_3\text{O}_{7-\delta}$ of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ for all of the Ln elements except for Ce, Pr, Pm, and Tb [131]. Research on the $\text{RBa}_2\text{Cu}_3\text{O}_{7-\delta}$ compounds progressed at an especially rapid rate throughout the latter half of 1987 and all of 1988. During this period, Japanese and U.S. efforts were comparable in terms of level of activity and research quality and accomplishments. On the materials front, Japanese researchers carried out some of the best work on the effect of transition metal substitutions on the superconductivity of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ [132], and the growth of single crystal specimens of $\text{RBa}_2\text{Cu}_3\text{O}_{7-\delta}$ compounds [133,134]. Some of the highest quality specimens

of $\text{LaBa}_2\text{Cu}_3\text{O}_{7-\delta}$, the most difficult of the $\text{RBa}_2\text{Cu}_3\text{O}_{7-\delta}$ compounds to prepare, have been fabricated by Japanese researchers [135,136]. Presently, the $\text{RBa}_2\text{Cu}_3\text{O}_{7-\delta}$ compounds are being actively investigated in Japan, especially with respect to the preparation of high quality polycrystalline and single crystal bulk samples as well as thin film specimens. Researchers in Japan are also actively pursuing the measurement of superconducting phenomena such as giant flux creep, oxygen disorder effects on T_c , upper critical magnetic fields H_{c2} , and critical current densities J_c .

3.5.3 $\text{Bi}_2\text{Sr}_2\text{Ca}_{n-1}\text{Cu}_n\text{O}_{2n+4}$ Compounds

Superconductivity with $T_c \approx 22$ K in the compound $\text{Bi}_2\text{Sr}_2\text{CuO}_6$ was discovered by Michel et al. in France in 1987 [123]. Independently, bulk superconductivity with $T_c \approx 8$ K was observed in the Bi-Sr-Cu-O system by Akimitsu et al. [125]. Shortly thereafter, Maeda et al. [11] in Japan reported superconductivity with onset temperatures near 110 K in the Bi-Sr-Ca-Cu-O system. Several superconducting phases with the compositions $\text{Bi}_2\text{Sr}_2\text{Ca}_{n-1}\text{Cu}_n\text{O}_{2n+4}$ have been identified with T_c 's of ~ 22 K, ~ 80 K, and ~ 110 K for $n = 1, 2,$ and 3 . Recently, Japanese researchers have succeeded in growing large single crystals of various compounds in the Bi-Sr-Ca-Cu-O system (e.g., $\text{Bi}_{2.0}(\text{Bi}_{0.2}\text{Sr}_{1.8}\text{Ca}_{1.0})\text{Cu}_{2.0}\text{O}_8$; $T_c \approx 92$ K [137]). Various chemical substitution experiments have been carried out; e.g., (1) with increasing Y concentration x in the $\text{Bi}_2\text{Sr}_2\text{Ca}_{1-x}\text{Y}_x\text{Cu}_2\text{O}_{8+\delta}$ system, superconductivity is suppressed and vanishes at $x \approx 0.5$, while an antiferromagnetic insulating phase occurs for $0.5 < x < 1$ [138], similar to what happens in the $\text{La}_{2-x}\text{M}_x\text{CuO}_{4-y}$ and $\text{RBa}_2\text{Cu}_3\text{O}_{7-\delta}$ compounds discussed above; (2) there appears to be an optimal hole concentration where T_c is a maximum in the $\text{Bi}_2\text{Sr}_2\text{Ca}_{1-x}\text{M}_x\text{Cu}_2\text{O}_{8+\delta}$ ($M = \text{Lu}, \text{La}, \text{Na}, \text{K}$) system [139]; and (3) substitution of F in the Bi-Sr-Ca-Cu-O system increases the volume of the "243" phase (at the expense of the "232" phase), raises T_c to 113 K, and results in the intergrowth of layers which contain different numbers of CuO_2 planes separating the BiO double layers [37].

An example where careful, systematic materials substitution work has led to new physics is illustrated in Fig. 3.1. This figure shows a logarithmic plot of the electrical resistivity versus temperature of $\text{Bi}_2\text{Sr}_2\text{Ca}_{1-x}\text{Lu}_x\text{Cu}_2\text{O}_{8+\delta}$ for various values of x ranging from 0 to 1 [139]. Of significance here is the dramatic change from superconducting to semiconducting behavior as x increases from 0.5 to 0.6, without showing a metallic non-superconducting phase. A similar effect was previously reported for the $\text{Bi}_2\text{Sr}_2\text{Ca}_{1-x}\text{Cu}_2\text{O}_{8+\delta}$ system [138], and has also been reported by Koike et al. [139] for other hole doping substitutions. High critical current densities $J_c \sim 10^6$ A/cm² at 77 K ($H = 0$) have been observed in thin films of $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_{10}$ [140]. Values of $J_c \sim 10^4$ A/cm² at 77 K

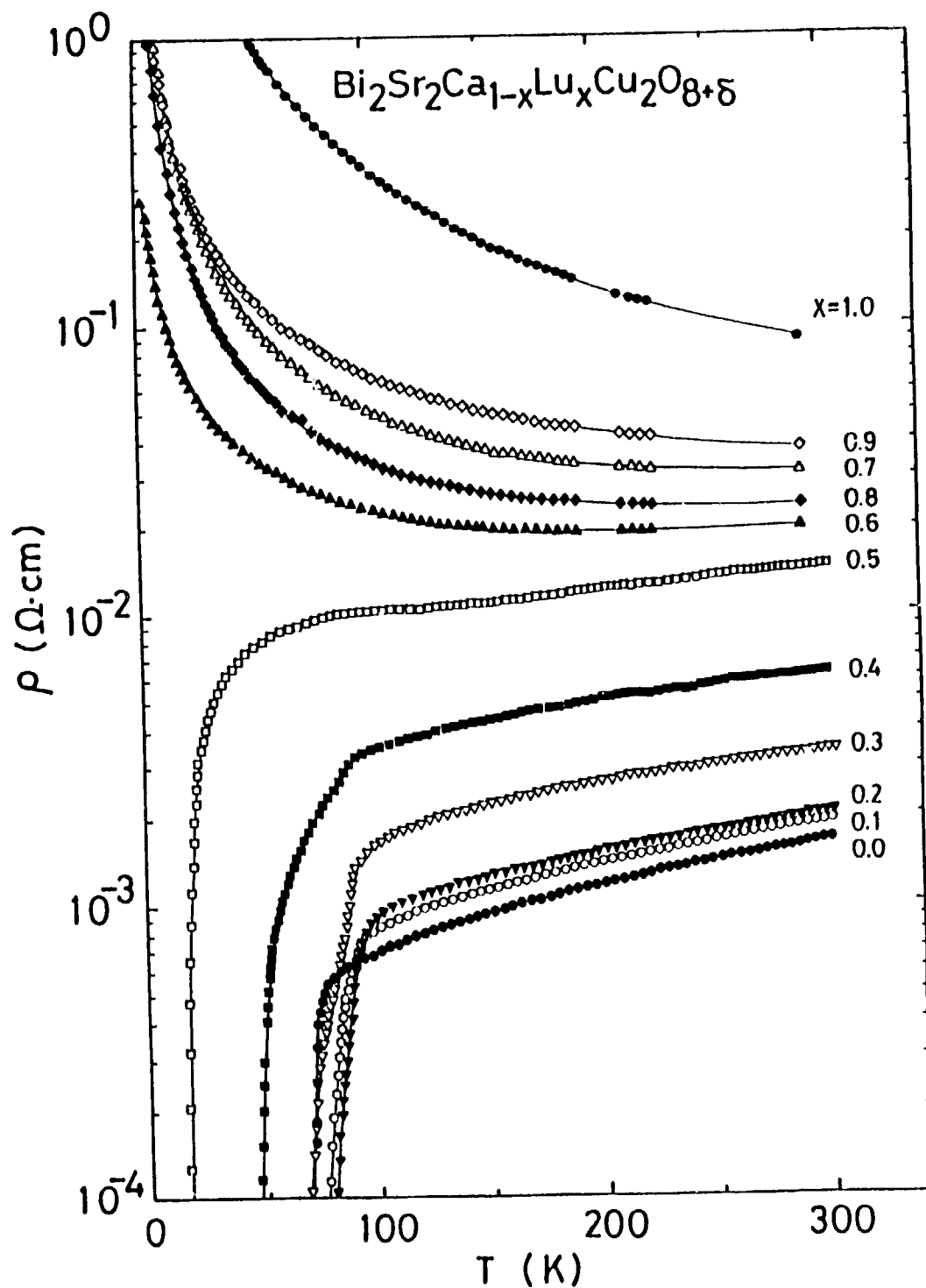


Figure 3.1: Logarithmic plot of the electrical resistivity versus temperature of $\text{Bi}_2\text{Sr}_2\text{Ca}_{1-x}\text{Lu}_x\text{Cu}_2\text{O}_{8+\delta}$ for various values of x ranging from 0 to 1. The transition from a superconducting metal to a nonsuperconducting semiconductor as x increases from 0 to 1 is evident in the data below ~ 100 K. After Y. Koike et al. [139].

which decrease by a factor of 10 in a field of 1 tesla have been observed in Ag-sheathed grain-aligned wires of the $T_c \sim 110$ K phase in the Bi-Pb-Sr-Ca-Cu-O system [15].

3.5.4 $TlBa_2Ca_{n-1}Cu_nO_{2n+3}$ and $Tl_2Ba_2Ca_{n-1}Cu_nO_{2n+4}$ Compounds

Superconductivity in the Tl-Ba-Ca-Cu-O system was discovered by Sheng and Hermann [105] in the U.S. in 1988 and, independently, by Kondoh et al. [141] in Japan. Several superconducting phases were identified shortly thereafter which have the compositions $Tl_2Ba_2Ca_{n-1}Cu_nO_{2n+4}$ with T_c values of 90 K, 110 K, and 125 K, for $n = 1, 2,$ and 3 [142]. These compounds are characterized by double TlO layers, separated by n CuO_2 layers which are, in turn, separated by CaO or BaO layers. Single TlO layer compounds with the formula $TlBa_2Ca_{n-1}Cu_nO_{2n+3}$ have been discovered by groups in Japan [32,33], the U.S. [143,144,145], and other countries [146,147]. Recently, several Japanese groups have succeeded in preparing single and double TlO layer compounds separated by n CuO_2 layers with n values up to 7. It has been found that T_c exhibits a maximum as a function of n at $n = 4$ for the single TlO layer compounds and at $n = 3$ for the double layer compounds (NRIM, Sumitomo, Tohoku University [12]). Shown in Fig. 3.2 are the crystal structures of single TlO layer $TlBa_2Ca_{n-1}Cu_nO_{2n+3}$ compounds for $n = 2, 3, 4, 5$ along with plots of the a -axis lattice constants and T_c versus number of CuO_2 layers per unit cell [12,32]. Superconducting thin films of $Tl_2Ba_2CaCu_2O_x$ on MgO substrates have been prepared with values of $J_c \approx 10^6$ A/cm² at 77 K ($H = 0$) [148]. Anisotropy of $H_{c2}(T)$ and the activation energy U_0 of the resistive transition curves has been investigated on a single crystal in the Tl-Ba-Ca-Cu-O system with $T_c = 106$ K [149]. Relatively large single crystals of compounds in the Tl-Ba-Ca-Cu-O system with dimensions of $2 \times 2 \times 0.1$ mm² and $T_c \approx 110$ K have been prepared at Sumitomo Electric.

3.5.5 $Ln_{2-x}M_xCuO_{4-y}$ ($Ln = Pr, Nd, Sm, Eu; M = Ce, Th; x \approx 0.15$) Compounds

One of the most interesting recent developments is the discovery of the electron-doped superconductors $Ln_{2-x}M_xCuO_{4-y}$ ($Ln = Pr, Nd, Sm; x \approx 0.15$) reported by Japanese researchers [8]. Shortly thereafter, four more related electron-doped materials were found by groups in the U.S.: $Eu_{2-x}Ce_xCuO_{4-y}$ ($x \approx 0.15$) [150], $Ln_{2-x}Th_xCuO_{4-y}$ ($Ln = Pr, Nd; x \approx 0.15$) [103,150], and $Nd_2CuO_{4-x-y}F_x$ [128]. These materials are of particular interest because the charge carriers responsible for the superconductivity appear to be electrons, rather than holes.

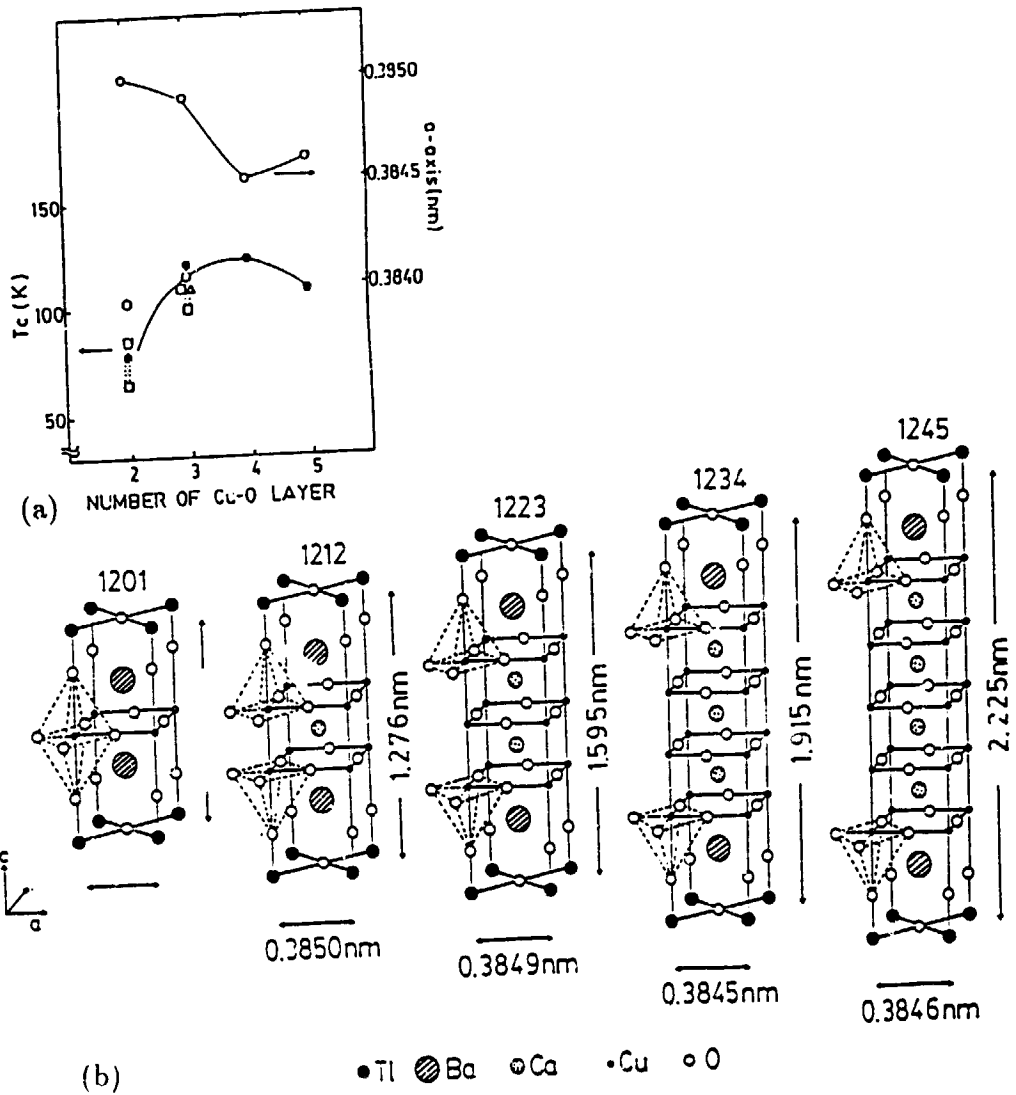


Figure 3.2: (a) Crystal structures of $TlBa_2Ca_{n-1}Cu_nO_{2n+3}$ compounds for $n = 1, 2, 3, 4, 5$ and (b) a -axis lattice constant and T_c versus number of CuO_2 layers in the unit cell. After S. Nakajima et al. [32].

that reside in the CuO_2 planes. The significance of the discovery of electron-doped high- T_c copper oxide superconductors may be several fold:

1. There appears to be a qualitative symmetry between doping the CuO_2 planes with electrons and holes; with increasing electron or hole concentration, the Cu^{2+} antiferromagnetism is suppressed, the materials continuously evolve from insulating to metallic, and superconductivity is induced.
2. The existence of electron-doped superconductors may place new constraints on the development of a viable theory of high- T_c superconductivity.
3. Electron-doping of CuO_2 planes may represent a new route to high- T_c superconductivity which may even result in the discovery of new oxide compounds with superior superconducting properties that are more suitable for technological applications than the materials now on hand.

Based upon these findings, it is possible to construct a generic phase diagram for the copper oxides which emphasizes the symmetry between electron and hole doping (see Fig. 3.3). Shown in the lower part of Fig. 3.3 are the schematic density of states curves corresponding to the various regions of the phase diagram.

The $\text{Ln}_2\text{CuO}_{4-y}$ parent compounds crystallize in a tetragonal " T' -phase" structure containing CuO_2 planes in which the copper ions are surrounded by a square planar arrangement of oxygen ions, in contrast to the $\text{La}_2\text{CuO}_{4-y}$ parent compound which forms an orthorhombic " T -phase" structure at low temperatures (below ~ 500 K) containing CuO_2 planes in which copper ions are surrounded by an octahedral arrangement of oxygen ions. The T' -phase and T -phase crystal structures are shown in Fig. 3.4 along with the related T^* -phase [8]. Whereas the CuO_2 planes in the T -phase can be doped with holes, but not electrons, the converse is true for the T' -phase, a result that seems to be associated with the missing apical oxygen ions in the T' -phase structure. However, it has not yet been established with certainty that the charge carriers involved in the superconductivity actually are electrons. Hall effect [151] and x-ray absorption spectroscopy [152,153] measurements on superconducting $\text{Nd}_{2-x}\text{Ce}_x\text{CuO}_4$ compounds have been interpreted in terms of electron doping of the CuO_2 planes, whereas electron energy loss spectroscopy experiments on this system indicate that there are holes at the oxygen sites [154].

GENERIC PHASE DIAGRAM FOR CU-OXIDES

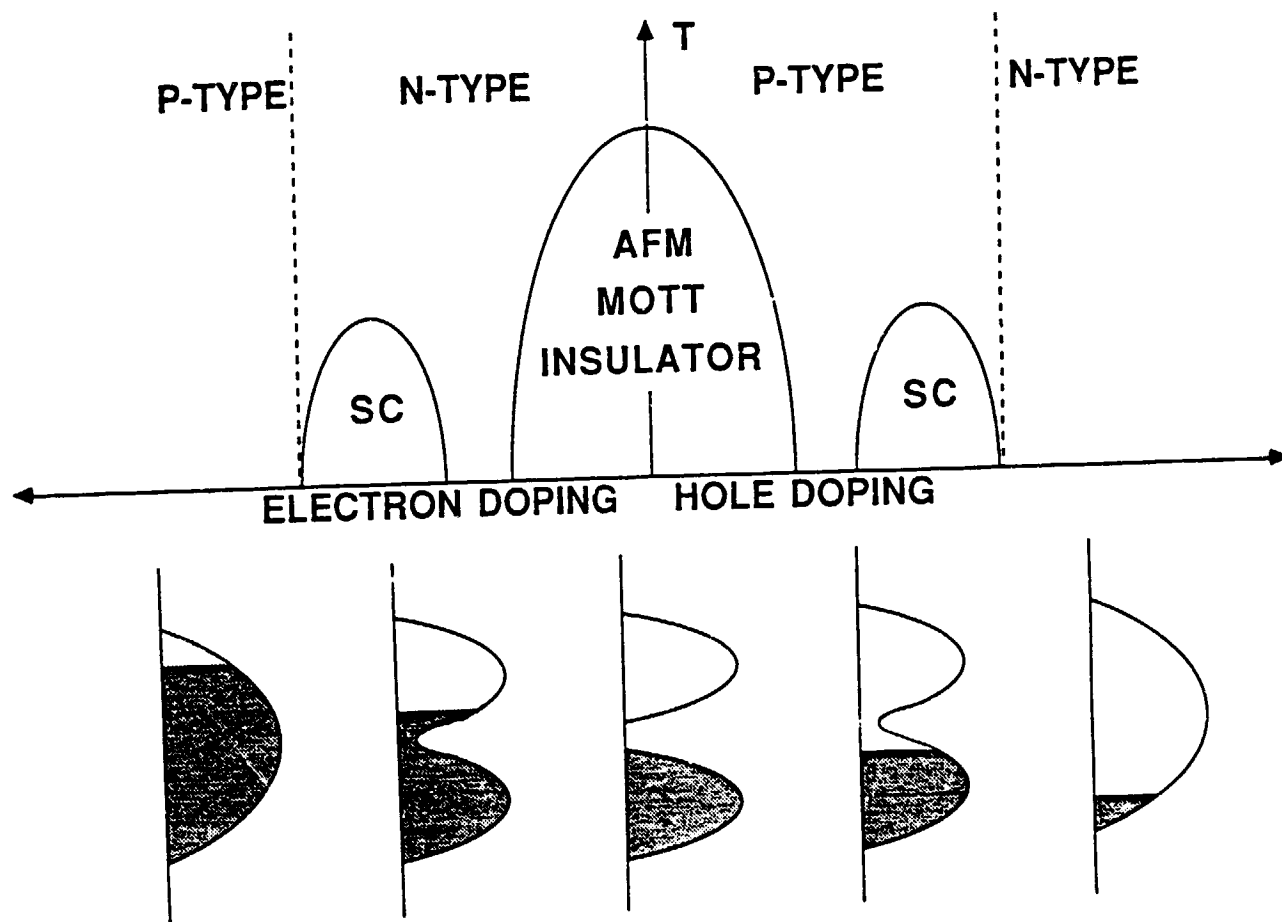


Figure 3.3: Generic phase diagram for copper oxides shown in the upper part of the figure. The schematic density of states curves for various regions in the phase diagram are shown in the lower part of the figure.

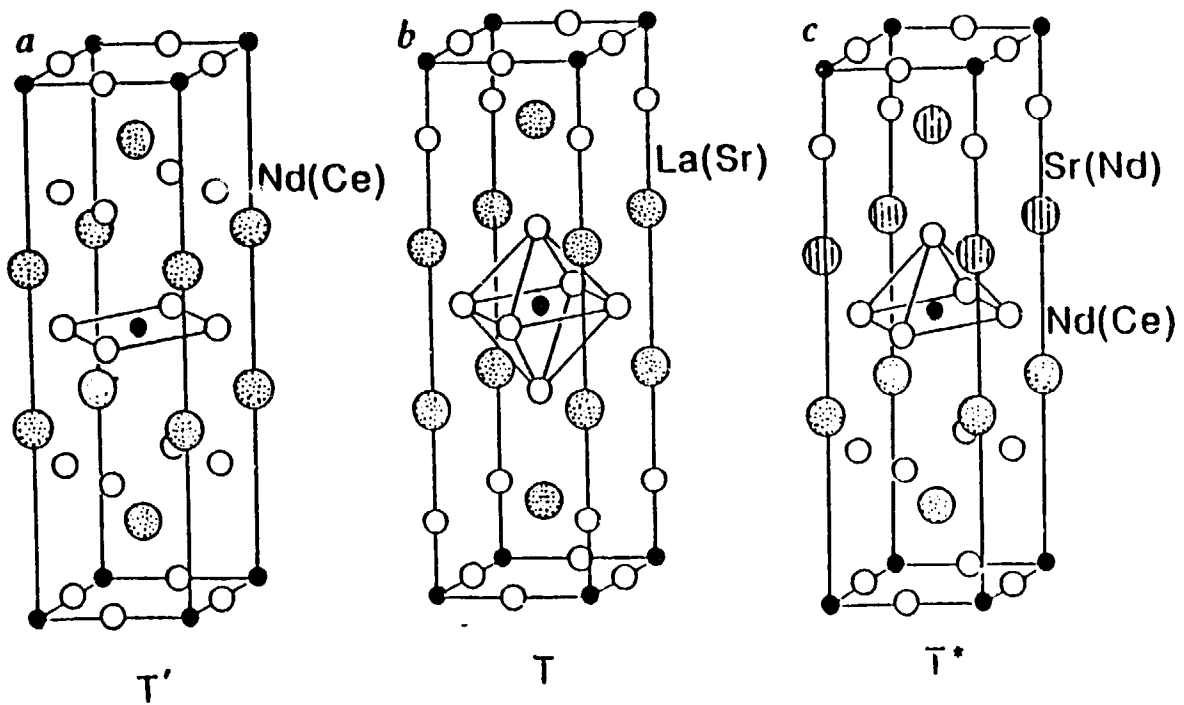


Figure 3.4: Crystal structures of various high- T_c phases: (a) $\text{Nd}_{2-x}\text{Ce}_x\text{CuO}_4$ (T' -phase), (b) $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$ (T -phase) and (c) $\text{Nd}_{2-x-y}\text{Ce}_x\text{Sr}_y\text{CuO}_4$ (T^* -phase). After Y. Tokura, H. Takagi, and S. Uchida [8].

3.6 Organic Superconductors

A substantial amount of effort on organic superconductors is being expended in Japan where there may be as many as twenty research groups (~ 100 researchers), in contrast with about five in the U.S. (~ 25 researchers), working on this subject. The research efforts in Japan are focused on synthesis, as well as the solid state physics and chemistry of organic superconductors. The interest in organic superconductors appears to be driven by the quest for higher T_c 's, a possibility that is suggested by the rapid rate of increase of the maximum value of T_c of the organic superconductors with time, which is even greater than that observed for oxides, although the maximum T_c of the organic superconductors is presently only about 11 K. The organic superconductor with the maximum T_c of ~ 11 K, the compound (BEDT - TTF) $_2$ Cu(NCS) $_2$, was discovered in Japan in 1988 by Urayama *et al.*[155]. The normalized electrical resistance $R(T)/R(273K)$ versus temperature and the crystal structure at 104 K of the organic superconductors (BEDT-TTF) $_2$ Cu(NCS) $_2$ are shown in Fig. 3.5 [155]. It is not inconceivable that the knowledge gained from research on the oxide superconductors may someday be used to "engineer" organic compounds in which the highest values of T_c will eventually be obtained. Japanese researchers are in an excellent position to capitalize on this possibility.

Japanese institutions in which research on organic superconductors is presently being conducted include:

- Synthesis
 - ISSP, University of Tokyo
 - Inst. for Molecular Science, Okazaki
 - Dept. Synthetic Chem., Osaka University
 - ISTECC, Tokyo and Nagoya
 - Sumitomo Electric

- Solid State Physics and Chemistry
 - Electrotechnical Laboratories;
 - Dept. Appl. Science, University of Tokyo;
 - Dept. Physics, Gakushuin University;
 - Dept. Physics, Kyoto University;
 - Inst. for Molecular Science, Okazaki;
 - Dept. Chem. and Dept. Physics, Toho University;

- Dept. Chem., Tokyo Metropolitan University;
- Institute for Materials Research, Tohoku University;
- Dept. Chem., University of Tokyo;
- ISSP, University of Tokyo;
- Dept. Chem., Tokyo Institute of Technology;
- ISTEK, Tokyo;
- Sumitomo Electric.

3.7 Heavy Fermion Superconductors

The so-called "heavy electron" (or "heavy fermion") superconductors are compounds of Ce and U which are superconducting at temperatures $T \leq 1$ K and have electron effective masses as high as several hundred times the mass of the free electron. These heavy masses are inferred from the enormous electronic specific heat coefficients that attain values as high as ~ 1 J/mole-K² [156]. The heavy electron superconductors presently known include CeCu₂Si₂, UBe₁₃, UPt₃, and URu₂Si₂. As stated in §3.2, this field was very active prior to 1986 both in the U.S. and Japan, but came to an abrupt halt with the advent of high T_c superconductivity. Although there is renewed interest in heavy fermion superconductors in the U.S., there presently appears to be only a low level of research on this subject in Japan (primarily at Tohoku, Tsukuba, and Hiroshima Universities).

3.8 Concluding Remarks

The JTEC Panel concluded that, overall, Japan places a substantially larger emphasis than the U.S. on materials research in their superconductivity program. A wide spread, but uncoordinated, search for new superconducting materials is underway, involving industrial, national and university laboratories. The Japanese have an extraordinarily strong research program on organic superconductors. Inter-laboratory collaborations in Japan in the area of superconducting materials research are still relatively weak, but are improving rapidly. The Japanese laboratories we visited are generally well equipped for research in superconductivity. Especially impressive has been the success of Japanese researchers in growing large, high quality single crystals which have been the object of basic research in both Japan and the U.S. Materials researchers are highly appreciated for their efforts in providing high quality polycrystalline, single crystal, and thin film specimens to other researchers and to

other experimental groups for collaborative efforts in characterizing the physical properties of these materials and in addressing important physical issues pertaining to the origin and nature of high- T_c superconductivity.

Chapter 4

Large Scale Applications of Superconductivity

John K. Hulm

4.1 Introduction

Large scale applications of superconductivity became feasible after 1961, with advances in liquid helium refrigeration technology and the discovery of high current, high field superconductors which led to the development of zero resistance high field magnets. These advances were made initially in the United States (Collins liquefier [157], high J_c materials [158]), although important scientific contributions were made in Great Britain (coherence concept [159]) and the USSR (Glag theory [160], vortices[160]).

The technology of high field superconducting magnets and their conductor materials made spectacular progress in the U.S. in the 1960's with the development of niobium-titanium and Nb_3Sn conductors in filamentary form, including stabilized conductors with copper and aluminum matrices. However, major contributions in the design of stable conductors were made in the U.K. (filaments [161]) and in Japan (diffusion process for A15 alloys [162]) in the late 1960's.

Japanese laboratories got off to a rather slow start in superconducting high field magnet technology, but by 1970 the three major Japanese electrical machinery firms and the cable and wire suppliers were rapidly coming up to par with the U.S. in both conductors and in magnet technology. Similar progress was achieved in Europe and in the USSR by the middle 1970's.

In the remainder of this chapter we will compare the present (1989) status of large scale, low- T_c superconductor technology in Japan with that in the

United States. The structure of the superconductivity industry and the national laboratories in both Japan and the U.S. will be discussed, together with an outline of major projects, materials development and the status of high field magnet laboratories in both countries.

While superconducting magnets constitute the main branch of this technology, another developing area is the direct use of the zero resistance property of superconductors in low magnetic field applications such as transmission lines and microwave cavities. The U.S. has led the world in power transmission experiments (Brookhaven [163]), but the technology has not yet found favor in the marketplace and the U.S. development has stopped. Large superconducting microwave cavities, on the other hand, have proved to be superior to normal metal cavities as regards energy loss, and superconducting cavities find growing use in linear accelerator technology. Advanced accelerators utilize multiple cavity resonators, not only for high energy physics and nuclear physics but also for medical applications and are likely to be important for other uses, e.g., free electron lasers. Cavities are presently made from niobium metal ($T_c \sim 9K$) cooled to 4.2K and must be free of surface imperfections and stress to yield high Q values. With solid Nb superconducting cavities, Q values around 10^9 have been achieved, compared to about 10^7 for copper cavities. Credit for initial success with this technology goes to West Germany [164], but Japan and the U.S. have both utilized such cavities in LINACS and both countries have made notable improvements in the technology recently [165,166].

While materials such as Nb, Nb-Ti and Nb₃Sn presently dominate the large scale applications, great interest exists in replacing them by the recently discovered oxide superconductors, cooled by liquid nitrogen. If equivalent electrical, magnetic and mechanical performance can be achieved with the new oxides, they will almost certainly replace the low- T_c superconductors because of the reduction in refrigeration and cryostat costs. Unfortunately rather severe problems exist in achieving adequate critical current density in high magnetic fields for the high- T_c oxides. A technological race between the U.S., Japan and Europe is now in progress on this problem. The outcome, if successful, will give the winner a considerable edge in more economic large scale applications of superconductors. The critical current problem is discussed in more detail in §3.3 of this report.

4.2 Administration of Large Scale Systems in Japan and the U.S.

Japanese progress in developing large scale systems utilizing low temperature superconductors has been steady and impressive over the past quarter cen-

ture. The key elements of this progress have been a well-integrated partnership between the following organizations:

- A group of government departments, including the Ministry of International Trade and Industry (MITI), the Science and Technology Agency (STA), the Ministry of Education (Monbusho) and the Japanese National Railways (JR). In close consultation with private industry, these government agencies originate, fund and provide overall coordination of advanced development projects, many of which utilize superconductors as a key sub-technology (see Table 4.1).
- A group of government laboratories operated by the above-mentioned departments which carry out a variety of functions including the development of new materials, testing of new systems, and technical coordination of projects. For superconductivity these national laboratories (and their sponsors) include
 - National Laboratory for High Energy Physics (Monbusho)
 - Electro-Technical Laboratory (MITI)
 - National Research Institute for Metals (STA)
 - National Institute for Research on Inorganic Materials (STA)
 - Japan Atomic Energy Research Institute (STA)
 - Railway Technical Research Institute (JR)
- Three large electrical companies (the "Big Three"), each with annual sales in the vicinity of \$20 billion, Hitachi, Mitsubishi Electric and Toshiba, are the main instruments of superconducting systems development in Japan. These major corporations now have a quarter century of experience in R&D on applied superconductivity and have supplied a large variety of development magnets plus cryogenic systems, including helium refrigerators, to government laboratories (see Table 4.1).

It is the expressed policy of the various government agencies and laboratories to rely on private industry to do most of the engineering and manufacturing of superconducting systems. There appears to be fierce competition between the suppliers to get these jobs (they regard them as technological "plums" and these Japanese companies are not deterred by the poor prospects for high manufacturing volume (in most cases). They are looking to utilize this newly acquired technology in the long-range future.

One area of low temperature superconducting magnet technology has gone beyond the R&D stage to commercial development, namely magnets

Table 4.1: Government sponsored large scale superconductivity superconductivity development in Japan.

Agency	Co-ordinating National Laboratory	Superconducting Applications
Ministry of Education (Monbusho)	High Energy Physics (KEK)	Dipoles, Quadrupoles, Detectors, Microwave Cavities
Ministry of Trade and Industry (MITI)	Electrotechnical Laboratory (ETL)	Josephson Junction Circuits, Generators (Super GM*)
Japan Railways (JR)	Railway Technical Research Institute (RTRI)	Maglev Train*
Science & Technology (STA)	Japan Atomic Energy Res. Inst. (JAERI)	Fusion Magnets
	Natl. Res. Inst. Metals (NRIM)	Advanced Superconducting Materials
	Natl. Inst. Res. Inorg. Matls. (NIRIM)	High- T_c Materials

* Major Projects

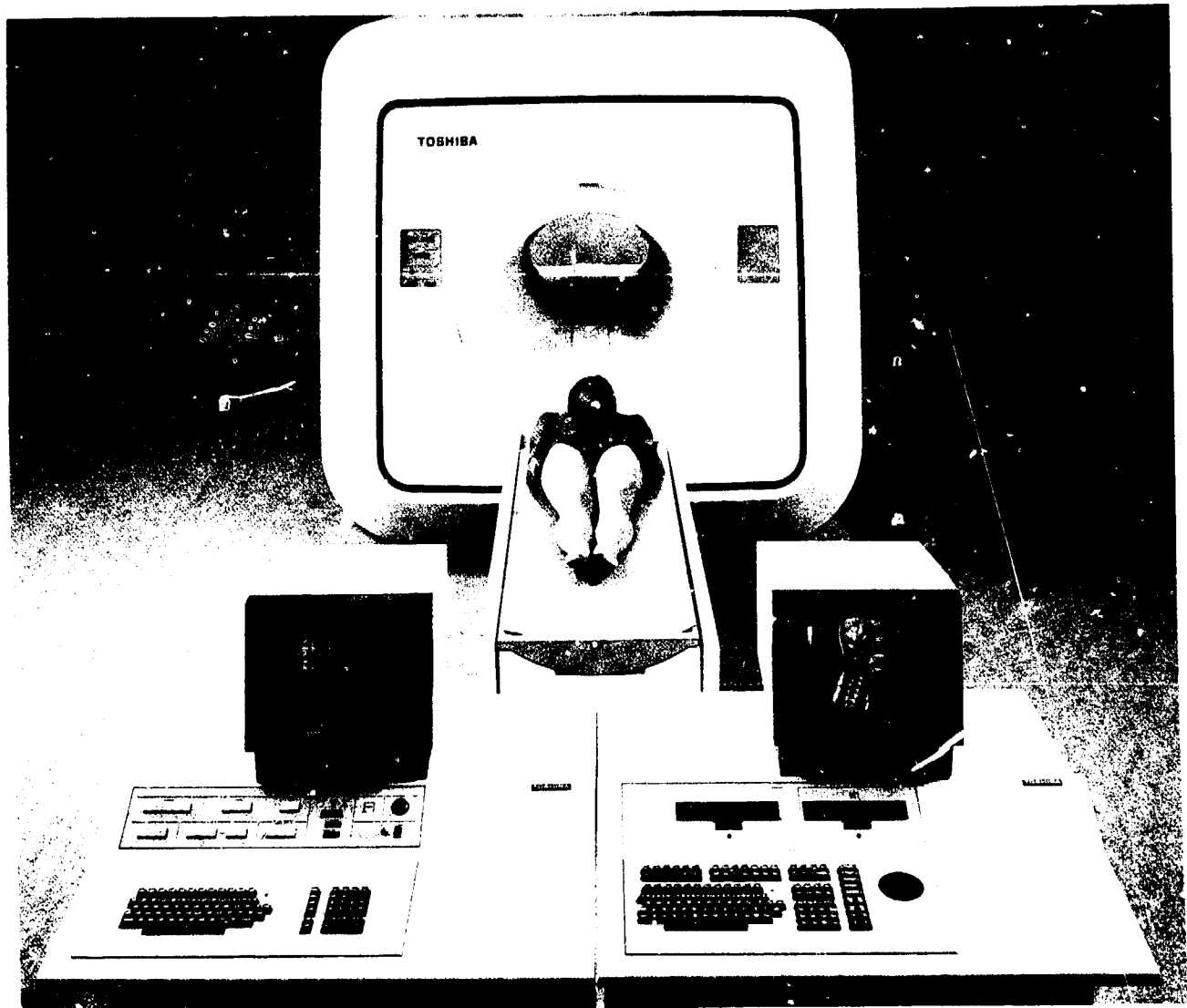


Figure 4.1: MRI whole body scanner with superconducting magnet (Toshiba).

for medical use in magnetic resonance imaging (MRI). All three major electrical companies have medical equipment divisions and through these outlets they are supplying MRI systems to Japanese hospitals. These systems are mainly constructed with large bore, high homogeneity, 2 tesla superconducting solenoids.

In a world-wide market of about 1,300 MRI systems sold to date [167], Japan appears to have approximately 200 systems in service. As far as we could determine in informal discussions, these appear to be split equally between Hitachi, Mitsubishi and Toshiba. A jointly owned venture between Furukawa and Oxford Instruments was said to have a few percent of this magnet market (as a component supplier). Marketing complete systems seems to be a key requirement for business success (see Fig. 4.1).

A potentially important future application of superconducting high field magnets lies in the generation of short wavelength x radiation for submi-

Table 4.2: Rough estimate of the numbers of full time researchers at the leading industrial laboratories.[†]

	Low- T_c	High- T_c
Hitachi	10	30
Mitsubishi	30	20
Toshiba	25	25
Sumitomo	4	21

[†]These numbers do not include engineers outside of R&D. In the case of Hitachi, the numbers in the table refer to the Hitachi Research Laboratory and there are about 30 additional researchers at Kokubunji working on superconductivity.

ron semiconductor integrated circuit manufacture. Synchrotron orbital radiation (SOR) for this purpose is generated by a compact accelerator using high magnetic fields for beam bending. Hitachi has constructed such a machine for NTT (see §4.3 for reference to the magnet for this machine).

- There are at least seven active suppliers of superconductor wires and cables to the various institutional development projects. Each of the electrical companies has its own captive materials supplier, while in addition there are several independent superconducting cable and materials suppliers, who, despite an order of magnitude sales lower than the "Big 3" electrical companies, have been aggressive developers of new low temperature ($< 25\text{K}$) superconductors. These include: Sumitomo Electric, Furukawa Electric, Fujikura and Kobe Steel. Sumitomo and Furukawa are broad-based advanced materials suppliers who strongly espouse the philosophy that the future of technology is heavily dependent on materials R&D. They are active in the marketing of products such as optical fibers, gallium arsenide and other advanced materials. The development program by Sumitomo Electric was found to be particularly impressive for high temperature (high- T_c) superconducting oxides.

Rough estimates of the numbers of researchers engaged in superconductivity research at several leading industrial laboratories in the superconductor industry are shown in Table 4.2.

The U.S. development program for large scale systems based upon low T_c superconductors is broadly similar to that of Japan in that most of the de-

Table 4.3: Government sponsored large scale superconductivity superconductivity development in the U.S.

Agency	National Laboratory	Superconducting Applications
Department of Energy	High Energy Physics Fermi Lab, Brookhaven SLAC, Cornell, SSC	Dipoles, Quadrupoles, Detectors, Cavities, CEBAF, RHIC, SSC*
	Energy Technology Brookhaven, Oak Ridge LASL, Sandia, LLL, Argonne, LBL, etc.	Fusion Materials, Conductors Low- T_c , High- T_c materials
Department of Defense	Wright-Patterson Naval Research Lab NSRDL Lincoln Labs, etc.	DARPA Projects Materials Electronics Power Devices
	SDI Office	Superconducting Magnetic Energy Storage*
Department of Commerce	NIST	J_c , R & Josephson Junction Stan- dards

* Major Projects

mand for superconducting magnets comes from government agencies engaged in advanced systems or technology development programs in which superconductors are merely a component. However, there are subtle differences between practices in the two countries which are worthy of comment.

- In the U.S., the principal source of funding for large scale superconducting development projects originates with two departments, DOE and DOD (see Table 4.3).
- The U.S. national laboratories, mainly funded through DOE, have served as the main instruments for the mounting of superconducting projects in high energy physics, fusion, magnetohydrodynamics (MHD), power transmission, etc. In some cases the engineering, design, and manufacturing of magnets is let out to industry, while in other cases the engineering work

and even limited production is carried out at the national laboratory. Some of these U.S. national laboratories have assembled large engineering teams to carry out this work. This is contrary to the practice in both Japan and Western Europe, and effectively weakens the experience base of U.S. companies. At the same time it has to be remarked that in contrast to the enthusiasm of Japanese industries for such development projects, many U.S. companies seem reluctant to tackle superconductor technology, especially for low- T_c superconductors, which these companies view as a narrow niche, low production opportunity.

- The industrial involvement in large scale superconducting projects is not restricted to U.S. heavy electrical companies such as General Electric and Westinghouse, but has also involved Aerospace companies, notably General Dynamics. At the same time, an array of smaller corporations in the less than \$200 million annual sales category have been attracted to or have been start-ups in the low- T_c , large scale superconductor applications area due to the lack of interest shown by larger corporations. Examples include General Atomics and Intermagnetics General.
- In great contrast to Japan, the superconducting materials suppliers in the U.S. are independent of the heavy electrical and aerospace giants. These relatively small superconductivity companies include Intermagnetics General, Oxford-Airco (British owned), Wan Chang-Teledyne and Supercon. It seems unlikely that the U.S. competitive position in superconducting technology has suffered as a result of this small company structure – indeed the U.S. suppliers have been able to adequately meet the market need for $< 10T$ sophisticated superconductors, mostly Nb-Ti alloys. However, after talking to the Japanese materials suppliers, we concluded that they are ahead of the U.S. in the development of advanced A15 and Chevrel phase conductors for the high magnetic field range, $> 15T$ (see §4.8.2). The market for such conductors is presently quite small, but apparently the Japanese are taking a longer range view, buttressed by the ability of their materials companies to support such R&D on account of their larger size and through active encouragement from government laboratories such as NRI.

4.3 Recent Large Scale Developments in Japan and the U.S.

As we have already stated, the technological experience of the Japanese “Big Three” electrical companies in superconducting magnets has been steadily

strengthened by a continuous stream of development projects rising from the government agencies and laboratories (see §4.2). A notable feature of these projects is that many of them are essentially long range, long time cycle activities, not subject to violent oscillations of government policy in areas such as energy, transportation, research, etc.

In our view, the Japanese are slow to start major new projects and they spend a great deal of time on getting a consensus between government and industry before they commit to a major new technology. However, once committed, the budget is set for many years and only technological or economic failure will stop the project. Of course, under the present Japanese rapid economic growth, it is relatively easy for the government to maintain and expand its commitment to development projects under Monbusho, STA, MITI, etc. However, even for the Japan National Railways (now JR), which has recently been through what amounted to bankruptcy (to the extent that this is possible for a national company), nevertheless, JR has maintained a large, long-term commitment to R&D on the magnetic levitation (Maglev) of trains.

The present United States situation is, of course, very different from that of Japan. The poor balance of trade and the national budget deficit, high welfare costs and military spending have all combined to make long-range budgeting for major development projects more or less impossible. Also, little or no consensus exists between government and industry on long-range technological policy. One piece of evidence for our inability to sustain long-range commitments is the long list of "stopped" projects involving large scale use of superconductors. This includes the Isabel accelerator (Brookhaven), abandoned after 4 miles of tunnel were constructed and a huge helium liquefier was installed, the mirror fusion test facility (Livermore) abandoned after the construction of a very large superconducting magnet, the superconducting transmission line (Brookhaven) a technological success rejected by the utility industry, and the superconducting generator (EPRI-Westinghouse) abandoned after partial rotor construction, for financial reasons.

It seems obvious that the U.S. has much to learn from the Japanese in project planning and in government-industry cooperation. This point has been well emphasized in many other American reports on Japan [168], so we will not belabor it here. However, it is quite remarkable that large-scale superconducting technology offers so many examples of project failure in the United States, and almost none in Japan.

We have already noted the broad experience of major Japanese electrical companies in superconducting projects. This is illustrated for Hitachi Ltd. in Table 4.4, where are tabulated representative magnets delivered in the 80's, the majority for development work. In some cases more than one system was delivered for a specific application. Most of these magnets operate at 4.2K.

Table 4.4: Characteristics of recent Hitachi large scale magnets.

Application	Customer	Type	Max Field, T	Bore [†] Size, cm	Year Delivered
Maglev	JR	Racetrack	5.1	300×80	1980
Fusion	JAERI	Tokomak	8.0	300×400	1984
	LCT [†]	Section			
Fusion	Univ. Kyushu	Full Tokomak	11.0	160	1986
Gyrotron	JAERI	60 GHz 200 kW	2.5	10	1984
High Energy Physics	KEK Fermilab	Detector Coil	1.5	286	1985
High Energy Physics	KEK	Beam Bending	10.4	-	1983
MRI	Hitachi Medical	High Homo. Solenoid	0.5	100	1984
High Field	Univ. Kyushu	Solenoid	15.5	10	1985
High Field Generator	NRIM MITI	Solenoid Saddle	18.0 6.0	18 -	1984 1983
Synchrotron Radiation	NTT	Beam Bending	-	-	1988

[‡]For non-circular bores, two figures are given

[†]LCT denotes large coil task

For our JTEC study a very similar list with minor variations, was prepared for Mitsubishi and Toshiba, but these lists are not shown here. It appears that the various agency customers are evenhanded in distributing development experience amongst the various companies, although the procurement activity is believed to be quite competitive and probably requires some investment by the companies themselves - particularly in areas of existing company business such as electric generators.

We assert that no single company in the United States has the breadth of magnet development experience represented by Table 4.4. General Dynamics, General Electric and Westinghouse have produced magnets in a few areas of Table 4.4, while General Atomics and Intermagnetics General have worked in other areas. In several instances the U.S. national laboratories have developed their own magnets or sought bids for materials and magnets from overseas. As noted earlier, this practice weakens the experience base of U.S. private industry, but industry can also be blamed for lack of aggressive action to build this experience base.

It is not possible or desirable for us to discuss every project in Table 4.4 in detail, but we will outline two Japanese development projects which are quite large in scope and involve each of the "Big 3" electrical companies. These are the Magnetic Levitation (Maglev) Train project and the Superconducting Generator project.

4.4 Maglev Trains

Seventeen years ago the Japanese National Railways (now JR), through its Railway Technical Research Institute (RTRI) in Tokyo, began an aggressive program to develop superconducting magnetic levitation of high speed passenger trains. This followed closely on the construction of a completely new steel rail passenger line between Tokyo and Osaka, the Shinkansen, which operates regularly at about 200 km/hr and carries over 100,000 passengers per day. The French TGV, operating between Paris and Lyon on a brand new steel track bed for most of this run, has achieved regular operating speeds in the 250+ km/hr range since 1980. It is the JR intention to enhance the Shinkansen to the 250 and 300 km/hr range as soon as possible.

Railway engineers doubt the capacity of steel rail vehicles to operate much above 300 km/hr, but it is well established that with a non-contact magnetic cushion, much higher speeds are possible. The RTRI has built a 7 kilometer test track on the coast of Kyushu Island, north of Miyazaki. Several experimental vehicles have been developed including ML100 and ML500, which operated on an inverted T (central beam) guideway, and MLU001 and MLU002 on a U-

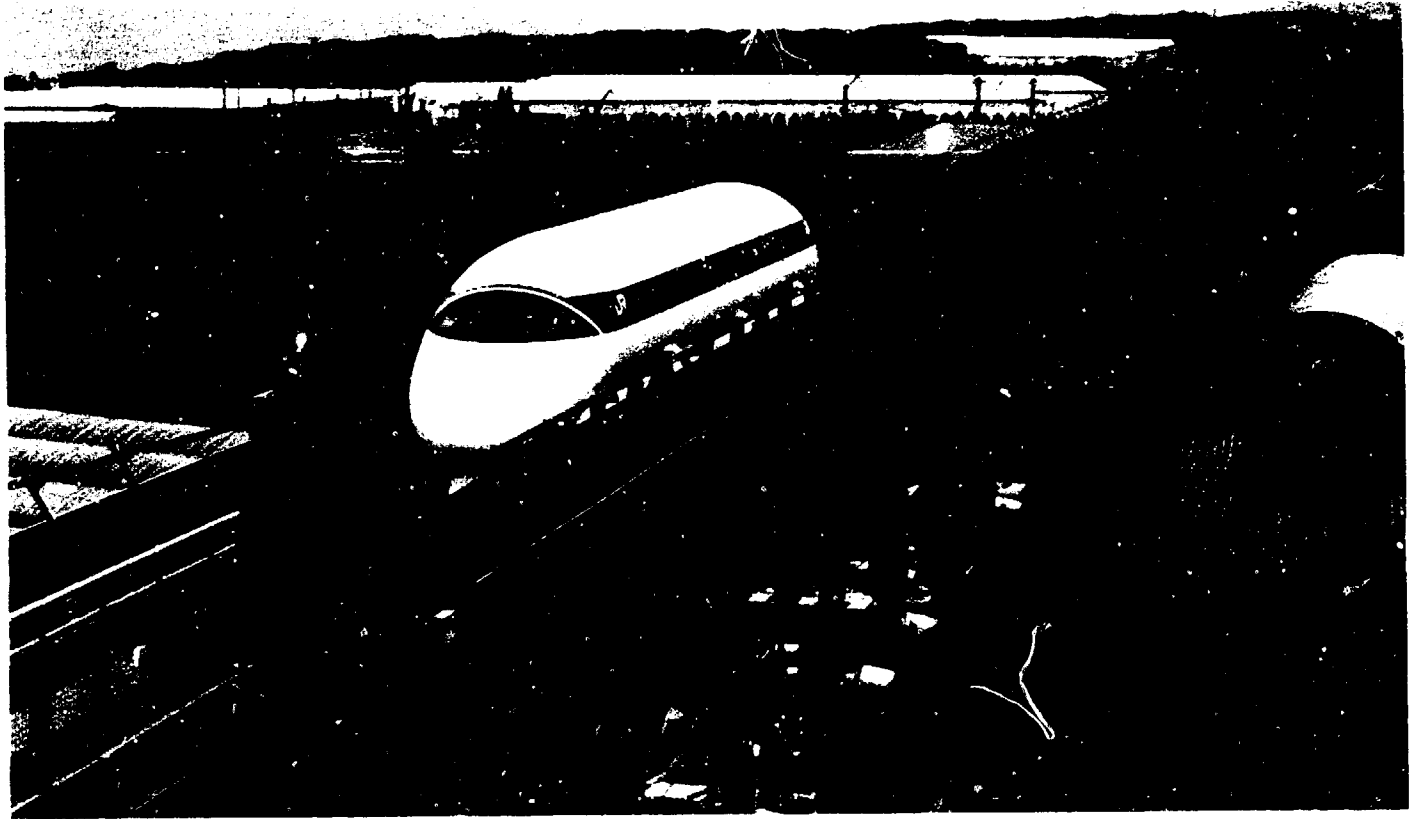


Figure 4.2: Magnetic levitation unit MLU002 (JR/RTRI)

shaped guideway, more like a standard railroad track, which is now preferred (see Fig. 4.2). Speeds of slightly over 500 km/hr have been achieved in test runs with ML500.

The MLU002 [28] can carry about 30 passengers and is mounted on two levitation bogies, one constructed by Mitsubishi and the other by Toshiba. Each bogie carries six superconducting magnets which are racetrack shaped dipoles mounted with the main field axis horizontal (maximum field 5.1 tesla), plus two refrigerators which supply liquid helium to the six coils. The magnets are operated in persistent mode (no input power) when in service (see Fig. 4.3).

Levitation is accomplished by a series of closed loop coils of normal material (copper or aluminum) placed at regular intervals along the track bed below each side of the car. The field of the on-board magnets induces eddy currents in the normal coils on the track bed and provides full levitation (10 cm) at speeds above 100 km/hr. Rubber-tired wheels are provided for landing at low speeds.

Horizontal guidance and vehicle propulsion is provided by a series of normal coils placed vertically at regular intervals along each side of the guideway. The field of the on-board superconducting magnets induces eddy currents in the guidance coils, providing a restoring force for any sideways motion of the car. The propulsion system is a linear synchronous motor, in which variable frequency, 3-phase power causes a magnetic pole to move along the vertical

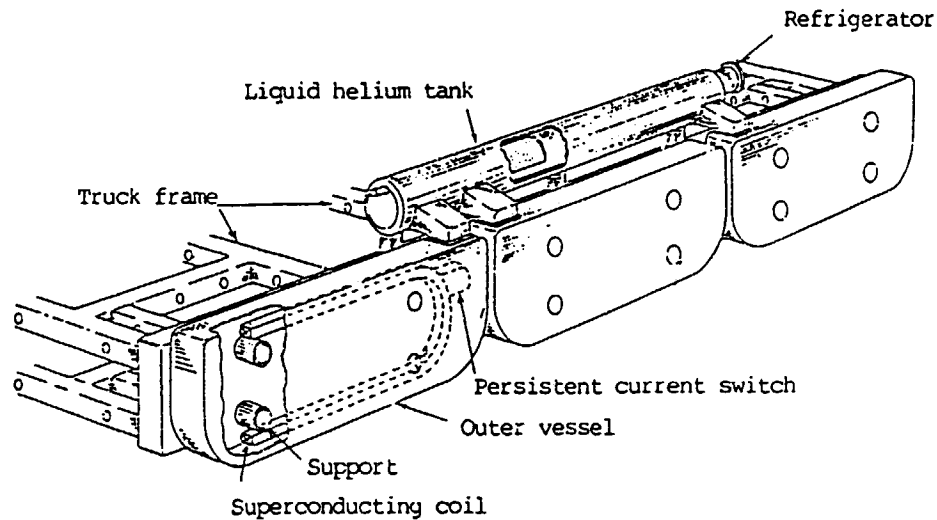


Figure 4.3: Refrigerator and three superconducting coils mounted on each side of bogie, MLUC-2 (RTRI).

normal coils of the guideway, and this pole moves the car by interaction with the superconducting magnets (see Fig. 4.4).

A great deal of experience has now been accumulated on the operation of the superconducting magnets and the various refrigerator systems which have been tested on the bogies. The JR engineers gave us a great deal of information on the detailed performance of the system. In a visit to ITRI, further discussions occurred on the engineering problems which lie in the path of constructing a full passenger line like the Shinkansen. These include electromagnetic drag at low speeds, how to get power on the cars for lighting, air conditioning, etc. and determination of the clearance required in tunnels for a vehicle moving at 500 km/hr.

At present JR is planning an extended test track of 50 km length. Possible sites considered for this test track at the time of the JTEC visit included an extension of the Kyushu test site, a possible airport-city link on the island of Hokkaido, and a site west of Tokyo which would ultimately form part of a new line from Tokyo to Osaka. The RTRI group seemed to favor the last-mentioned proposal as the most realistic approach to a new high traffic density system, but they remarked that there was much political pressure for the first two sites. The discussion reminded me of the site selection process for the SSC! Subsequent to our visit, the government selected a 50 km route within the Yamanaichi prefecture between Tokyo and Osaka for the test track.

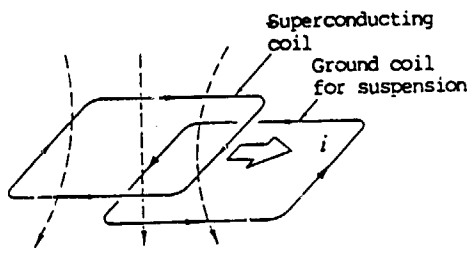


Fig. 1 Electrodynamic suspension

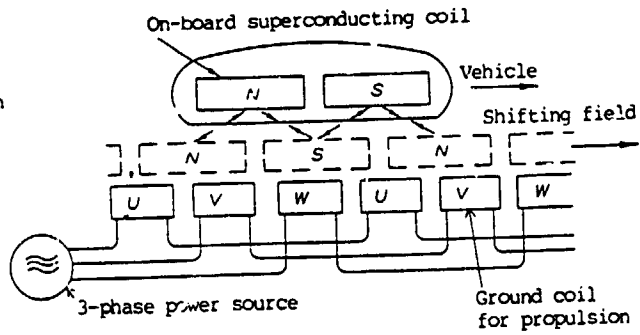


Fig. 2 Linear synchronous motor

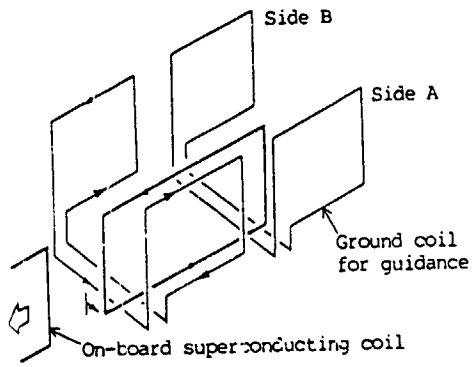
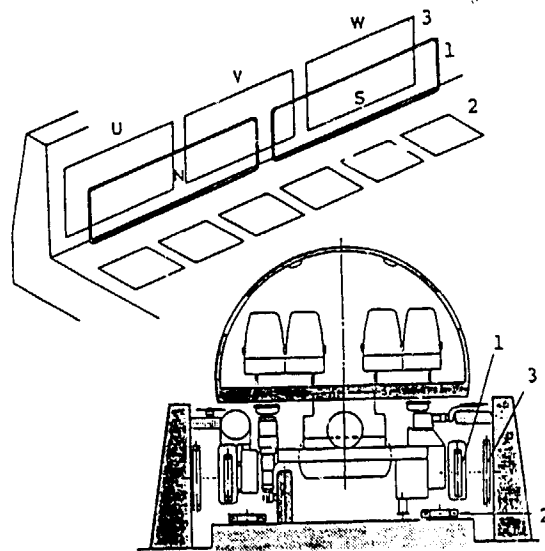


Fig. 3 Null-flux magnetic guidance



- 1: Superconducting coil
- 2: Ground coil for suspension
- 3: Ground coil for propulsion and guidance

Figure 4.4: Principles of the magnetic suspension, guidance and propulsion system, MLU002 (RTRI).

4.5 Superconducting Generators

In present-day commercial turbine-generators for power generation, a large d.c. magnet, which is an integral part of the rotor, is driven by a steam or gas turbine at 50 or 60 revolutions per second. The rotating d.c. field, thus produced, sweeps over a set of 3-phase coils on the stator (outside the rotor), generating 3-phase power output which passes through a step-up transformer to the grid system. Power levels in the 100 to 1,000 Megawatt range are typical for modern stations.

About half of the power loss in the generator, which is around 1% of the total power generated, is dissipated in the copper windings of the rotor magnet. This creates an opportunity for the use of a superconducting magnet in the rotor, which would not only create substantial power savings over the life of the machine (typically 30 years) but would also eliminate massive cooling systems which are required to remove the rotor power dissipation from the interior of a normal machine. Due to the higher exciting field of the superconducting magnet, savings are expected through size and weight reduction. System stability is also improved.

Experiments on small superconducting generators have been carried on in the U.S., Japan, West Germany, France and the USSR since the early 1970's. For much of this period the U.S. was ahead in the technology, but the usual "hare and tortoise" scenario emerged in which the U.S. "hare" sat down to rest in 1983, while the Japanese and German "tortoises" continued their steady progress towards practical machines via a set of long-term development programs.

The Japanese experience is based upon what appears to be steady, partial funding from MITI over the entire period after 1974. Mitsubishi and Fuji Electric constructed 6.25 MVA (1976) and 30 MVA (1983) (see Fig. 4.5) machines [169], Hitachi a 50 MVA unit (1983)[170] and Toshiba a 3 MVA machine for component testing (1983). The years shown here represent the completion of tests. After 1983, Mitsubishi performed studies on a model, 1/4 scale rotor for a 1000 Megawatt machine. For these studies, a study group together with a subordinate working group were organized with members from universities, government and private research institutes, electric power companies, plus manufacturers of electrical machinery, electric cable, refrigeration equipment and materials.

The published results of these studies are worth quoting [171]:

1. The superconducting generator will be superior from the total economic point of view, because of such advantages as the reduction of the power losses to half those of conventional generators, improved operating char-

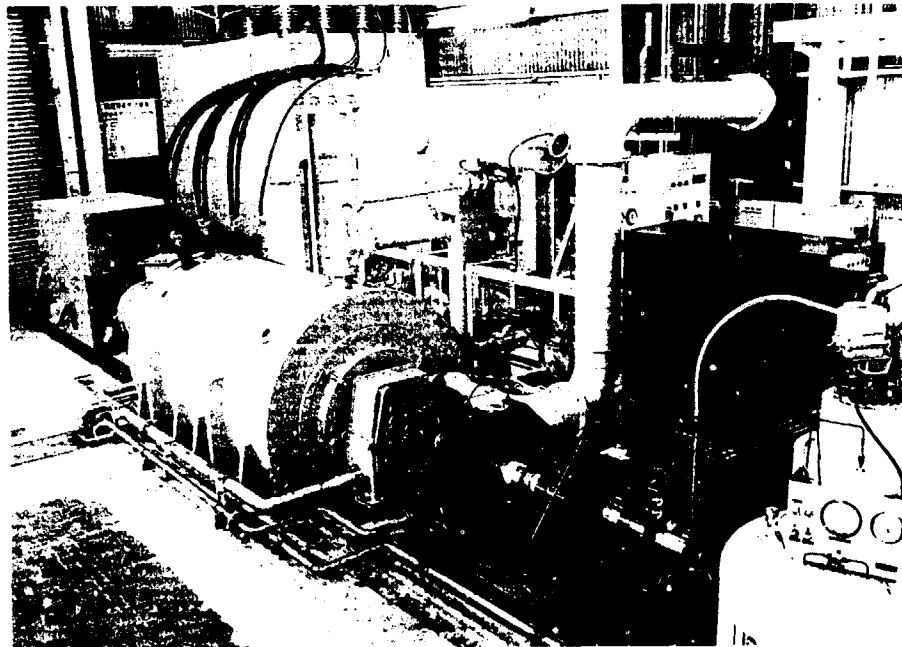


Figure 4.5: 30 MW superconducting generator (synchronous condenser) (Mitsubishi Electric).

acteristics, improved power systems stability as well as reduced manufacturing cost due to its reduced size and weight.

2. The superconductor and cryogenic technology can apply to a wide range of electric power technologies with great merits. These highly promising new technologies will be able to meet the various requirements of electric power systems in the future. They will also have pervasive effects leading to the creation of a new industrial field with wide applications.
3. The development of a practical superconducting generator is considered to be possible, provided that systematic and strong R&D efforts are mounted in a well-organized national project.

These recommendations were taken seriously by MITI, who set up an Engineering Association for Superconductive Generation Equipment and Materials (Super GM) in 1987 to handle a 10-year development program. The members of Super GM are:

- Generator manufacturers: Mitsubishi, Hitachi, Toshiba
- Electric power companies: Tokyo, Chubu, Kansai
- Central Research Institute for Electric Power
- Electric cable companies: Sumitomo Electric, Furukawa Electric, Fujikura, Kobe Steel
- Refrigeration equipment manufacturers: Toshiba, Mitsubishi
- Japan Fine Ceramics Center (Nagoya)

This group actually reports to the New Energy Development Organization, essentially a trust under MITI which handles the new generator project as part of the so-called "Moon Light" project.

The Super GM project is presently in the stage of component tests. For example, at ETL we saw a rotor from Toshiba which will be rotor B in a 70 MW machine targeted for manufacture between 1990 and 1993. After 1995, the project will move on to a 200 MW machine to be manufactured and tested in the remaining 5 years of the 20th century.

The Japanese power industry expects to adopt superconducting generators for thermal plants after 2000 AD and for nuclear plants after 2015, and it is expected that this technology will be utilized in all new power plants after 2030. None of these plans depend upon success with the high- T_c oxide superconductors; it is presently assumed that liquid helium cooled low- T_c superconductors will be used to achieve the stated goals.

Unfortunately there is no national program on superconducting generators in the United States. As pointed out earlier, the U.S. 270 MW superconducting generator project was abandoned in 1983 and we know of no plans to revive this effort in the U.S. Perhaps, if the Japanese or European projects are successful, the U.S. power industry will be able to import such machines from overseas, a sobering thought.

Turning now to U.S. large-scale superconducting projects, we should note first of all the great success of superconducting magnets in magnetic resonance imaging (MRI) systems. These magnets are vital components of the majority of the ~ 1000 MRI systems already installed in the U.S. American companies have participated strongly in this business.

There are two important large-scale national projects in the U.S., the Superconducting Supercollider (SSC) and the Superconducting Magnetic Energy Storage project. For comparison with Japanese projects, these will be briefly reviewed.

4.6 Superconducting Supercollider (SSC)

This machine is an advanced synchrotron accelerator to be located in Texas, near the Dallas-Fort Worth area. The plan is to accelerate two separate, oppositely traveling proton beams up to 20 TeV before bringing the beams into collision with each other. The accelerator ring will be approximately 53 miles in circumference in an underground tunnel. Beam bending and focusing will be achieved by 5,000 dipole and quadrupole superconducting magnets in each ring. According to present designs the magnets utilize Nb-Ti alloy in a cabled structure, with 6 micron filaments of superconductor embedded in copper strands.

All magnet development work to date (since 1985) has been performed at Lawrence Berkeley Laboratory (LBL), Brookhaven National Laboratory (BNL), and Fermilab. However, private industry will be invited to bid on manufacturing the magnets in the near future. It is not yet clear whether foreign vendors, for example the Japanese, will be allowed to bid on this work. The total cost of the magnets will be close to one billion dollars, an attractive manufacturing opportunity.

A further complication is that the Japanese government (and presumably Monbusho) has been invited by DOE and by the Board of Overseers of SSC to join in the project as a scientific partner, along with making a major contribution of financial support to the project. It is not yet clear what Japan will do in this regard, but it seems likely that any appreciable investment on their part will carry with it a "quid pro quo" on development work.

During our tour of Japan there was an opportunity to visit the high energy physics center (KEK) at Tsukuba where we had conversations on superconductivity with Dr. Hiromi Hirabayashi, Director of the Engineering and Scientific Support Division at KEK, who said that they had explored the construction of various cosine theta magnets of the general type proposed for the SSC. In reviewing the present SSC design, they concluded that while it had the merit of being the lowest cost design in terms of material used, the insertion of wedges in the coil was a disadvantage as regards ease of manufacture. It was the view of this Japanese design team that a wedge-free coil, would be a better overall choice and they have prepared such a design. It would seem that a scientific collaboration between the U.S. and Japan in the research on the SSC would be enhanced by a U.S.-Japan cooperation in the design of the machine, including such vital components as the superconducting magnets.

4.7 Superconducting Magnetic Energy Storage

The possibility of the loss-free storage of energy in high current density, medium magnetic field, high volume superconducting coils was conceived after the realization of high field, high current density conductors in 1960. Studies and small-scale experiments have been carried out in Japan and the U.S. with the objective of using such coils for the storage of electrical energy in electric power systems. The goal is to store energy during off-peak consumption and to utilize this energy in peak periods of consumption, thus reducing the needed level of installed generating capacity.

To be of economic value to a typical U.S. power complex, a storage system should be able to handle energy in the range from about 1,000 to 10,000 Megawatt-hr. The largest energy stored in a superconducting magnet system to date is about 0.3 Megawatt-hr, (large coil tokamak (LCT) fusion system). Hence there is a very large gap in technological experience which must be bridged.

Fortunately there is a requirement for an intermediate level of stored energy under the Strategic Defense Initiative (SDI) which needs electrical pulse power for beam weapons. In this connection SDI has commissioned two independent teams of U.S. contractors to perform design work on liquid helium cooled, Nb-Ti alloy coils to store energy at about the 30 Megawatt-hr level. This program is presently in the study phase and the actual construction of storage magnets may not take place for at least two years.

Other possible applications of storage magnets have been suggested. For example, JR is believed to be considering the use of superconducting magnets as trackside power sources for the Maglev train.

4.8 Recent Advances in Low- T_c Conductors in Japan and the U.S.

Most superconducting magnets are constructed from multi-filamentary (MF) superconductor threads embedded in a so-called stabilizer material, usually pure copper or aluminum. The superconductor filament diameter is usually $20\ \mu\text{m}$, or less, depending on the dynamic requirements placed on the magnet (rate of change of field or a.c. frequency). The use of fine filaments reduces the local magnetization energy density due to high critical current density in the material, which in turn cuts down on the energy loss due to flux jumps. This prevents the triggering of normal zones in the magnet.

Magnets fall into two categories, fully stabilized coils where the ratio of stabilizer area to the superconductor area is large (> 100), and partially stabilized coils where the stabilizer to superconductor ratio lies between 1 and 2. The selection of this ratio is largely determined by the coil geometry. The low current density available in the fully stabilized case is not acceptable for many types of applications; usually space or weight considerations force the designer to use a partially stabilized winding. In this type of magnet, if the maximum J_c is exceeded, the magnet quenches, its temperature rises, and there is a loss of field for a period determined by how long the system takes to cool down again. This is not a dangerous event; it is simply inconvenient.

Figure 4.6 (adapted from data of the Hitachi Research Laboratory) shows the field and current regions in which the various magnet types of Table 4.4 were designed. Apart from fusion and high field research magnets, the other magnets operate in the field range below 10T and utilize Nb-Ti superconductors. Indeed, more than 90% of the superconducting magnets constructed to date have used Nb-Ti conductors. Despite the relative maturity of Nb-Ti technology, improvements and advances have recently occurred in both the U.S. and Japan.

4.8.1 Nb-Ti Conductors

Critical current density is a vital parameter in the construction cost of the SSC magnets, since the magnet materials constitute about one-third of the magnet cost. An intensive development program on Nb-Ti conductors has been carried out over the past four years at the University of Wisconsin, LBL and BNL (Fig. 4.7). Critical current densities, J_c , at 5T has been raised from around $2 \times 10^5\ \text{A/cm}^2$ to about $2.8 \times 10^5\ \text{A/cm}^2$, by attention to the homogeneity of the alloy billets and to the heat treatment cycle. As Fig. 4.7 indicates, these improvements have not only been achieved by three of the U.S. based suppliers,

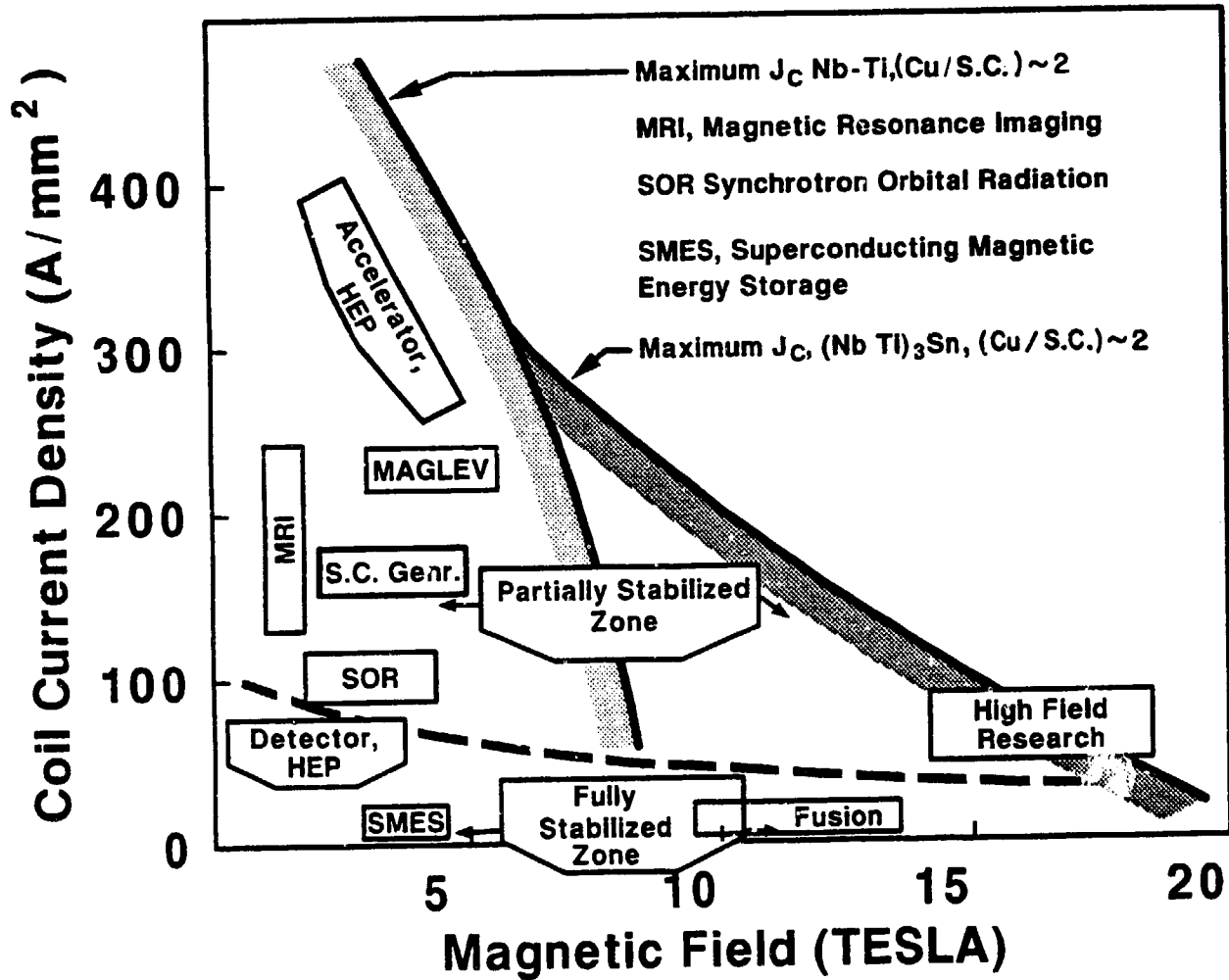


Figure 4.6: Stabilization practice, magnet types (Hitachi).

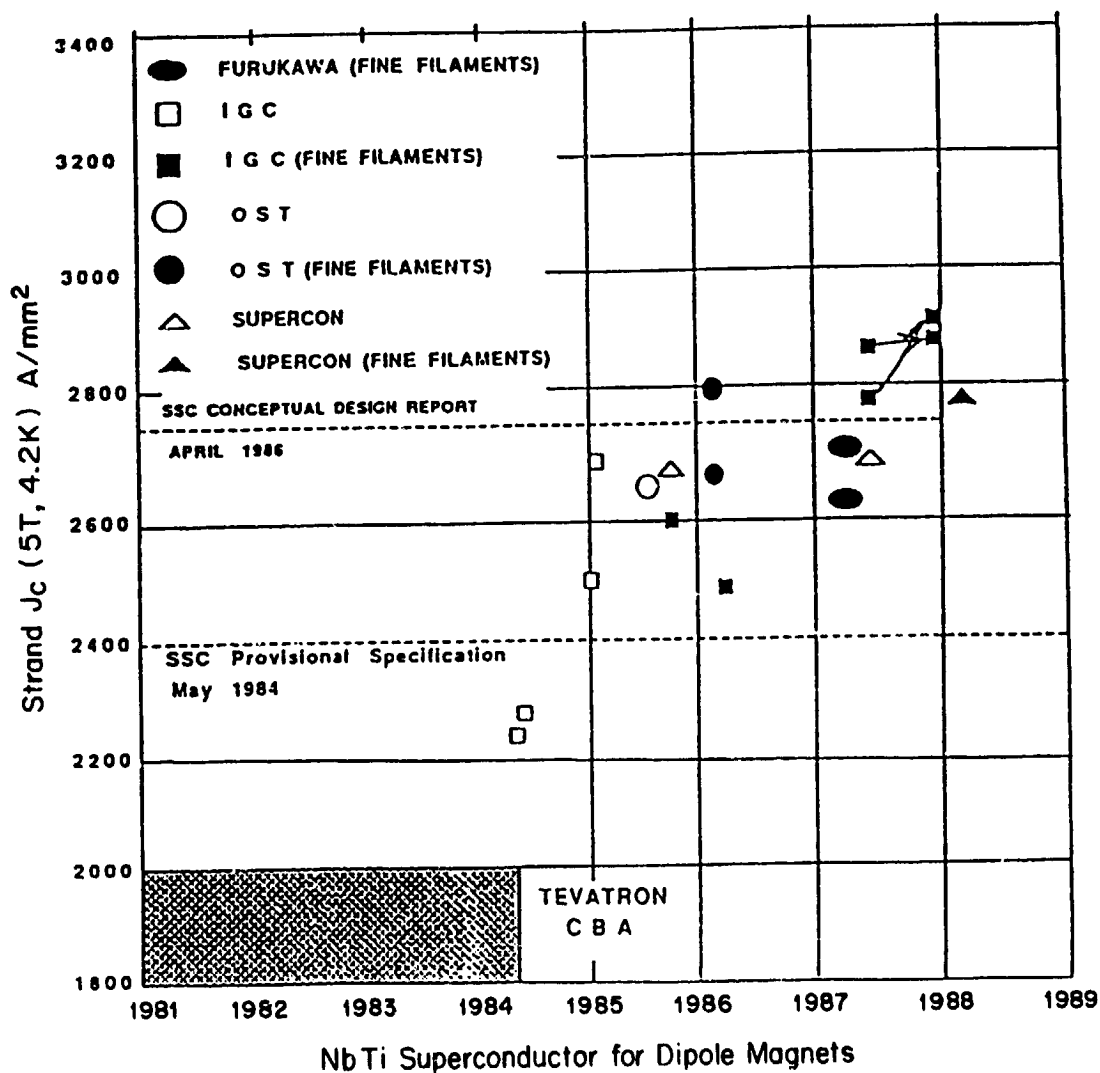


Figure 4.7: Recent advances in J_c for Nb-Ti superconducting material for the SSC. Production lengths refer to wire lengths long enough to make a magnet for the superconducting supercollider (SSC). Here IGC, OST and CBA, respectively, denote Intermagnetics General Corporation, Oxford Superconducting and colliding beam accelerators.

but also by Furukawa Electric. Similar material was indicated to be available from Sumitomo Electric.

As the filament size declines below 20 μm , the cost of the multifilament (MF) material increases, but certain improvements in electrical properties accrue. The a.c. and dynamic losses decline more or less continuously down to filament sizes of about 0.5 μm . The residual magnetization of the conductor also decreases, which is important for an accelerator with a sweeping field starting from zero. Both of these effects are expected for type II superconducting material of fixed critical current density, according to the Bean model of the magnetization and the area of the hysteresis loop [172].

For filament sizes below 0.5 μm , other phenomena besides simple type II magnetization become important. These include the proximity effect and type I current penetration of the filament surface. Both of these tend to raise the electrical losses with decreasing filament diameter. However, there is a lack of understanding of the basic loss mechanisms in this region of filament size, and it is possible that even lower losses could be produced with further development.

It was our impression that most of the Japanese materials suppliers have carried out R&D on filaments down to the sub-micron range. Their goal is probably connected with the development of electric power equipment such as the superconducting generator discussed in §4.5. We were told at NRIM that both Sumitomo Electric and Furukawa had achieved good MF material in production at 0.5 μm . It was also indicated that R&D studies were made for filaments as small as 0.03 μm . Although some work has been carried on for submicron filaments in the U.S., it was the JTEC Panel's impression that the effort was considerably larger in Japan.

4.8.2 A15 and Chevrel Phase Conductors

The utility of Nb-Ti alloys falls rapidly above 10T and in this field region other materials must be considered. In the U.S. there has been a good deal of development work on Nb₃Sn-based conductors, utilizing the so-called "bronze process". In this process, a composite of Nb-metal and Cu-Sn alloy is first extruded and drawn to MF strands, and finally Nb₃Sn is formed as a last step by diffusion of tin out of the bronze into the Ni filaments. Materials of this general type have been used in some experimental dipoles for the SSC and one of the six coils in the LCT system was a force-cooled (as opposed to bath-cooled) Nb₃Sn conductor. However, the U.S. experience in the 10T and 20T field range, although the U.S. represented the leading world effort in this range before 1970, has since been lacking in diversity. Perhaps this can be attributed to the fact that the market for super-field materials is negligible (if one does not take the long-range view) and that the U.S. high field (research) magnet

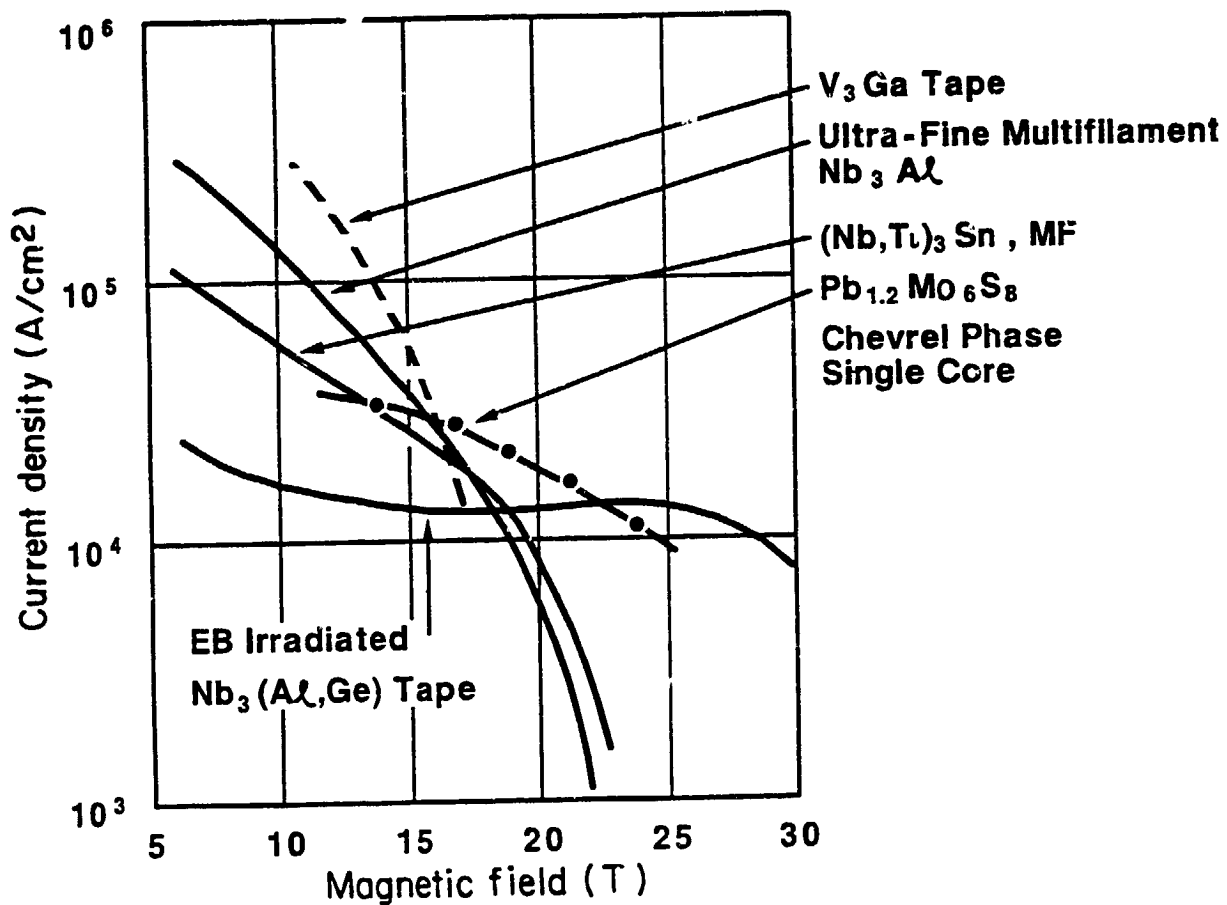


Figure 4.8: Current density versus magnetic field for various advanced high field conductors from various sources.

effort has suffered slow strangulation at the hands of the National Science Foundation.

A completely different situation exists in Japan. The NRIM laboratory is famous for its pioneering work in developing A15 conductors and much of this technology has been successfully transferred to the Japanese materials suppliers.

In our visit to NRIM the JTEC team was briefed on a process for producing very fine multi-filamentary conductors of Nb₃Al, with final filament size around 1,000 Å [173]. This process depends upon drawing down a tube of Ni filled with Al, 10% Mg alloy. The hardness of the Al-Mg alloy is comparable with that of niobium, not only when annealed but also after cold-working. Wire formed from a single tube is cut into short sections and rebundled to form a multi-filamentary composite. The final step is a diffusion reaction to form Nb₃Al filaments at 700-1000°C. It will be necessary to add stabilizer to the system to achieve a practical conductor, but nevertheless the J_c versus H data show great promise for this material (Fig. 4.8). In addition it was found that the J_c value of the new Nb₃Al conductor was less sensitive to mechanical stress than in the case of multifilamentary Nb₃Sn. Indeed, the reduction of J_c per unit strain was observed to be about three times lower for Nb₃Al than for Nb₃Sn.

A selection of J_c versus H curves for other A15 conductors developed in Japan is shown in Fig. 4.8. We cannot discuss all of these materials in detail; our purpose here is to point out the broad approach which the Japanese laboratories have adopted to the high field range. The work on the single core Chevrel phase wire was carried out at the Mitsubishi Electric Laboratories, and achieved quite high J_c values for this material ($\sim 2 \times 10^4 \text{ A/cm}^2$ at 20 tesla) [174].

4.9 High Magnetic Field Research Facilities in Japan and the U.S.

High magnetic field research facilities are important for solid state research in a number of important fields, including research on both low temperature and high temperature superconducting materials. There are two general categories of equipment. First, magnets which provide steady or d.c. fields; these extend at the present time to just over 30 tesla. Second, pulse magnets which provide large peak fields for short times. We shall discuss these two categories separately.

4.9.1 High Field Magnets

In the case of steady magnetic fields, there are two types of equipment, first totally superconducting coils, which have achieved slightly over 20T maximum (KFK, W. Germany) and second water-cooled solenoids (Bitter, polyhelix) which also can achieve over 20T. By placing a water-cooled normal solenoid inside of a superconducting coil (so-called hybrid magnet), the maximum field has been increased to around 30T, with plans for fields up to 45T in the future, although the technology for this has not been fully developed. Of course, the working bore is an important parameter for such magnets, and, to some extent, bore size can be traded for increased field. Installations of this type require substantial investments in power supplies, water-cooling facilities and helium liquefaction systems. Consequently, there is only one such dedicated facility in the U.S., the Francis Bitter National Magnet Laboratory (FNML), at MIT, in Cambridge, MA. A similar facility exists at Tohoku University, Sendai, Japan. Both of these laboratories have several stand-alone water-cooled and superconducting magnets for experiments up to 20T, but hybrid systems are utilized for higher field experiments in both laboratories (Table 4.5). MIT is currently constructing a Hybrid III system which will reach 35T in a 33 mm bore. Tohoku has set essentially the same goal for their facility.

MIT has plans on the drawing board for a 32 mm, 45T magnet, but this will require a major investment in a larger power supply (20 MW) and other

Table 4.5: High magnetic field d.c. hybrid facilities in Japan and the U.S.

Location		Bore (mm)	Max field (tesla)
Tohoku, Sendai	Hybrid 1	32	31
	Hybrid 2	52	23
	Hybrid 3	32	20
MIT, Cambridge	Hybrid II	33	31.8

facilities for which funds are not yet available.

A proposal to Monbusho to improve the Sendai facilities is apparently being prepared. In addition, a completely new high field facility will be constructed at Science City (Tsukuba) with plans for developing a 40T hybrid magnet, a > 20T all superconductor magnet and an 80T short-pulse magnet.

To summarize the Japan versus U.S. situation for d.c. fields, the U.S. facilities at present seem to be comparable to those in Japan or Europe, and the immediate plans for Hybrid III, 35T, will maintain this comparability. It should also be said that the FBNML User program is really outstanding in the provision of high field services to the science community, whereas Tohoku seems to have relatively fewer users.

It also seems obvious that unless new funds are provided at FBNML, the facilities will eventually be outstripped in the next decade by European and Japanese developments, particularly those planned for Tsukuba. The JTEC Panel was given no details on these plans during our visit to the present Tsukuba facilities.

4.9.2 Pulsed Field Magnets

In Japan the largest facility for producing pulsed magnetic fields is a dedicated facility known as the Megagauss Laboratory, part of the Institute for Solid State Physics, University of Tokyo. The principal equipment in this laboratory consists of a set of capacitor banks ranging in size from 200 KJ up to 5.0 MJ, an elaborate switching and control system and various experimental stations with massive protective enclosures to contain the energy release from the magnet coils.

The following techniques are utilized for pulse field generation:

1. Discharge of 200 KJ through a multi-turn, filamentary reinforced copper solenoid which is nondestructive, to some extent, and yields a field of 50+ tesla, for a time duration of ~5 ms.
2. Discharge of 1-2 MJ through a single-turn copper coil yielding fields of 200+ tesla for a time duration of ~ 4 ms (coil destroyed, sample may be saved).

3. Discharge of 5 MJ into a special flux compression pair of coils but the sample is destroyed, yielding a field of 350+ tesla for a time duration of ~1 ms.

Aside from the armored enclosures for the exploding coils, special arrangements are made to ground the electronic systems in this laboratory. This laboratory is the best equipped pulsed field facility in the world and has allowed the Japanese to make pioneering contributions to research on high field properties of oxide type superconductors.

A megagauss laboratory on the scale of that at ISSP undoubtedly involves initial costs of several million dollars. However, useful pulsed fields of somewhat lower magnitude can be achieved with smaller capacitor banks for well below \$1 M. Such facilities exist at several other locations in Japan, including Osaka and Sendai.

Although pioneering work on pulsed magnetic fields was done in the U.S. in the 1950's, the United States still lacks a dedicated pulsed high magnetic field laboratory. For many years pulsed magnet work has been carried out at the Francis Bitter National Magnet Laboratory (MIT) using type (1) multiturn technology. In fact, FBNML holds the world's record for millisecond duration fields, based on Dr. S. Foner's niobium-filament, reinforced copper solenoid which attained a maximum field of 68 tesla. It is understood that several Japanese laboratories are in the process of adopting this technique. The present U.S. efforts at the FBNML are innovative, but could almost be described as "token efforts". A new initiative for a special, dedicated Megagauss facility seems urgent in the U.S.

4.10 Summary

1. Large scale applications of superconductivity throughout the world are presently based upon low temperature superconducting materials such as Nb-Ti and Nb₃Sn. It is expected that these materials will be gradually replaced by conductors fabricated from the new high temperature oxide superconductors. Both Japan and the U.S. are extremely active in R&D aimed at this goal.
2. With the exception of magnetic resonance imaging (MRI), which is the principal commercial application of superconductors at the present time, large scale superconductive application products are mainly supported by government funds and coordinated by national laboratories in both Japan and the U.S. The scale of activities is comparable in both countries.
3. In Japan at the present time there are two major (~\$100 M) development projects, superconducting magnetic levitation for trains (maglev) and superconducting electric generators, both aimed at specific commercial markets. The U.S. also has two major projects, but one of these is aimed

at basic science, the Superconducting Supercollider (SSC), while the other is intended for a combined defense/commercial goal, the Superconducting Magnetic Energy Storage (SMES) system.

4. Japan Railways has successfully developed a superconducting magnetically levitated vehicle which has achieved speeds exceeding 500 km/hr. However, very extensive engineering development and an enormous capital investment will be necessary to bring the present embryonic system to main line railroad standards. There is no comparable U.S. activity.
5. MITI has formed a consortium of Japanese manufacturers and utilities to develop prototype superconducting electric generators at about 70 and 200 Megawatt output in the next decade. Extensive experience exists throughout the world with smaller experimental machines of this type; the project is quite conservative. Developments of such systems are presently suspended in the U.S.
6. The U.S. Congress has tentatively authorized DOE to build a 53 mile circumference synchrotron accelerator in the Dallas-Fort Worth area. This machine, the SSC, will accelerate two separate counter-rotating proton beams up to about 20 TeV before collision. The 10,000 superconducting dipole and quadrupole magnets required will constitute by far the largest superconducting project ever attempted. DOE has to persuade other countries, experienced in superconducting technology to participate in this project, especially Japan.
7. Two prototype superconducting magnetic energy storage coils at about the 30 Megawatt-hr level are under design by two separate industrial teams in the U.S. The project is supported by the Strategic Defense Initiative (SDI) as an energy source for beam weapons, but systems of this type are also of interest for peak-shaving in electric utility systems.
8. The large scale projects discussed so far are highly dependent for success upon the availability of sophisticated, complex superconductors from materials suppliers. In the U.S. there are essentially 4, more or less domestic suppliers, whereas in Japan there are at least 7 suppliers of which 3 are subsidiaries of large electrical manufacturing companies. This disparity has not prevented the U.S. from maintaining a competitive position in Nb-Ti conductors, from which over 90% of superconducting magnets are constructed. However, the Japanese presently dominate the market for high field materials in the region above 15 T.
9. High magnetic field research facilities are vital for R&D work on superconductors, semiconductors, etc. At present, the Japanese and American facilities are comparable for steady fields up to about 30 tesla. The Japanese have a pulsed magnetic field facility at the University of Tokyo which is superior to anything in the U.S.

Chapter 5

Processing of Superconducting Materials

Rod K. Quinn

5.1 Introduction

Large scale applications of superconductivity (see Chapter 4) such as magnets for high energy physics experiments, magnetic resonance imaging (MRI), superconducting generators, and superconducting magnetic energy storage (SMES) require superconducting materials in forms useful for manufacturing these devices. The development of processing techniques for the production of Nb-Ti multifilamentary wire for the winding of superconducting magnets opened the door for application of the "conventional" low- T_c materials to the production of high field magnets.

Large scale application of the high- T_c superconducting (HTSC) oxide ceramics will also require the development of processing techniques to form these materials into conductors such as wire, tape, or monolithic shapes. There are several materials-related issues critical to achieving such development of practical conductors fabricated from the high- T_c oxides. These materials are ceramics, and by their very nature they are brittle and difficult to form into shapes such as wire and tape, useful for bulk conductor applications. Aside from this obvious problem, the critical issue that confronts every processing scheme is the ability to form the material or its precursors into a final net shape that can carry a technologically practical current density.

The critical current density J_c of the conductor as a function of applied magnetic field is the figure of merit for applications-oriented processing of the high temperature superconducting phases, and a target of $J_c = 10^4$ A/cm² at liquid nitrogen temperature (77 K) and 2 tesla applied field is often quoted as

a medium-term goal to make high temperature superconductivity compounds interesting from an applications standpoint [175]. The critical current J_c is strongly affected by a number of materials-related parameters such as structural features, which include grain boundaries, defects, and second phase inclusions, both within grains and at grain boundaries. Many or all of these features may directly affect the magnitude of flux-pinning forces that allow current to flow through superconducting materials. At this time, little is known about the mechanisms of flux pinning in the high temperature superconductivity materials. However, through much research over the past two years, it has become apparent that several processing strategies are necessary to accommodate these materials parameters and improve the J_c 's in the high temperature superconducting materials. Specifically, the processing strategies must be directed toward achieving a high density material, a high degree of intergranular orientation of the ab plane of these perovskite compounds along the direction of current flow, and the materials processing must result in minimal grain boundary contaminants that may act as weak links in the conductor, thereby reducing J_c .

5.2 Techniques for Processing High Temperature Superconductors

Worldwide, the processing of high temperature superconducting materials into monoliths, wires, and tapes has largely concentrated on the superconducting phases $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ ($T_c = 93$ K), and the structurally related families of Bi-Sr-Ca-Cu oxide ($\text{Bi}_2\text{Sr}_2\text{Ca}_{n-1}\text{Cu}_n\text{O}_x$ ($n = 1, 2, 3$), $T_c = 80 - 110$ K) and Tl-Ba-Ca-Cu oxide ($\text{Tl}_m\text{Ba}_2\text{Ca}_{n-1}\text{Cu}_n\text{O}_x$ ($m = 1, 2$; $n = 1, 2, 3$), $T_c = 90 - 125$ K), as well as the Pb-substituted analogs of the latter two families. Each of the compounds contained within these families has a significantly different chemistry, and thus significantly different processing strategies may apply. Because these phases are prepared at relatively high temperatures ($850^\circ - 950^\circ\text{C}$) and are thermodynamically metastable, maintaining phase purity during processing is a challenge.

For the $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ compound, the superconducting properties are significantly affected by the oxygen stoichiometry which is in turn a function of temperature. In addition, oxygen diffusion rates are quite low in this compound [176]. Therefore, when processing $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ to a dense ceramic form, the ability to achieve adequate oxygen concentrations is often difficult: thus, achieving proper oxygen stoichiometry must be factored into the processing strategy. In the thallium system, thallium oxides are volatile under typical processing conditions. Because loss of Tl from the superconducting phase is deleterious

to its properties, any processing strategy for the Tl family of superconductors must address this problem.

Many classical processing techniques have been attempted to produce monolithic conductors, wires, and tapes in addition to a few novel techniques. A recent review has outlined the necessary processing parameters and strategies [177], and much has been published on this topic. A summary of the most important techniques that have been studied in the U.S. and Japan follows. Representative examples and references will be found in Tables 5.1 (for the U.S.) and 5.2 (for Japan).

5.2.1 Processing of Monolithic Conductors

Most of the processes examined to date are based upon densification and alignment of grains in sintered powder compacts of $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ ("123") [178,179,180,194,195]. Hot pressing at high temperatures and the application of uniaxial pressures have produced pellets of superconducting, textured material. Another promising process is melt textured growth (MTG) that relies on partial melting of $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ followed by directional solidification in a thermal gradient [179]. Because the high- T_c superconducting materials have a preference to grow more rapidly in the *ab* plane, the directional solidification results in highly textured, dense, large-grained materials. The slow crystallization from the liquid also tends to exclude second phases from the grain boundaries. A modification of the MTG process is quench melt growth (QMG), where $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ is taken well above its peritectic melting point to form Y_2O_3 plus liquid (see Fig. 5.1), and the material is then quenched rapidly to low temperature [194,195]. This process results in the formation of small nuclei of Y_2O_3 within the matrix. In a second step, the material is once again rapidly taken to slightly above its melting point and then is directionally solidified. This process results in dense, large grained, highly textured materials that have very small inclusions of a second phase of Y_2BaCuO_5 ("211") distributed within the grains. It is thought that these small nuclei may act as flux pinning centers. These melt texturing processes are being studied both in the U.S. and Japan.

5.2.2 Processing high- T_c superconductors to Form Wires and Tapes

A widely practiced approach to the preparation of clad tapes or wires involves filling a metal tube, usually silver, with the desired high- T_c superconducting oxide or oxide precursors, swaging the tube closed, and then drawing the diameter of the tubing down to form wire. The wire or tape is then sintered in

Table 5.1: Representative benchmark data for wires, tapes, and thick films of high- T_c superconductors in the U.S.

Laboratory	Process	Conductor Properties	Comments
U. Houston, Texas Center for Superconductivity	Controlled cooling of melt through $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ peritectic (1°C/hr).	$J_c = 15,000 - 18,500 \text{ A/cm}^2$ @ 77K, 0T; $J_c = 75,000 \text{ A/cm}^2$ (pulsed) @ 77K, 0T; $J_c = 37,000 \text{ A/cm}^2$ (pulsed) @ 77K, 0.6T	Ref. [173]. Dense, highly oriented
AT&T Bell	Melt-textured growth. Directional solidification of $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ melt	$J_c = 17,000 \text{ A/cm}^2$ @ 77K, 0T; $J_c = 4000 \text{ A/cm}^2$ @ 77K, 1T	Ref. [179] Dense, textured bars, $1 \times 2 \times 30 \text{ mm}^3$
AT&T Bell	Hot forging of $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ powder at 1000°C , 26 MPa, 6 hr.	$J_c \sim 3000 \text{ A/cm}^2$, T unspecified	Ref. [180] Textured pellet
Stanford U.	Laser heated pedestal growth of Bi-Sr-Ca-CuO _x fibers	$R = 0$ @ 80-85K J_c (pulsed) = $60,000 \text{ A/cm}^2$ @ 68K	Ref. [181] Highly oriented fiber, with ab plane along fiber axis
Argonne National Laboratory	Tape cast $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ powder with and without Ag powder. Tape placed onto Ag foil substrate, followed by sintering	$R = 0$ @ 86-90K; $J_c = 300 \text{ A/cm}^2$ @ 77K	Ref. [182] $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ / Ag composite; good mechanical properties
Superconductor Technologies, Inc.	Spin-on composition of Tl-Ca-Ba-Cu 2-ethylhexanoates deposited onto substrates	$R = 0$ @ 100K, $R_s = 250 \text{ m}\Omega$ @ 77K, 150 GHz. No J_c reported	Ref. [183] Textured, $3 \mu\text{m}$ films on (100) MgO or YSZ
Massachusetts Institute of Technology	Spin-on process of Pechini-citrate/ethylene glycol polymerization mixture for Bi-"4334" films on (100) SrTiO ₃	$R = 0$ @ 70-75K $J_c = 5 \times 10^5 \text{ A/cm}^2$ @ 4K, 0 T	Ref. [184] $0.5 \mu\text{m/coating}$
IBM-Yorktown Heights	Spin-on composition of Y, Ba, Cu trifluoroacetates dissolved in methanol. Various substrates.	$R = 0$ @ 91K; $J_c = 10^4 \text{ A/cm}^2$ @ 77K, 0T on LaGaO_3	Ref. [185,186] Cu Laser patterning of "green" film
Microelectronics and Computer Technology Corporation	Spray pyrolysis of Bi-Sr-Ca-Cu nitrates onto (100) MgO and BeO. Post deposition melt-quench-anneal to densify film. Bi-"2212", "4334" stoichiometry.	$R = 0$ @ 81K; $J_c = 4000 \text{ A/cm}^2$ @ 77K on (100) MgO	Ref. [187] $3 \mu\text{m}$ thick film
Sandia National Laboratory	Screen printing of $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ powder ($5 \mu\text{m}$) dispersed in an alcohol. Printed onto substrates.	$R = 0$ @ 91K; $J_c = 93 \text{ A/cm}^2$ @ 76K	Ref. [188] $300 \mu\text{m}$ films
Los Alamos National Laboratory	High-rate magnetron sputtering from single target Tl-"2212" and "2223" targets	$R = 0$ @ 90K; $R_s = 6 - 7 \text{ m}\Omega$ @ 15K, 22GHz; $25 \mu\text{m}$ thick films. No J_c reported	Ref. [189] $20-25 \mu\text{m/h}$ deposition rate

Table 5.2: Representative benchmark data for wires, tapes, and thick films of high- T_c superconductors in Japan.

Laboratory	Process	Conductor Properties [†]	Comments
Sumitomo	Ag-sheathed tubes drawn to wire, then cold rolled to tapes	(Bi,Pb)SCCO-0.14×4 mm ² tape: $J_c = 1.7 \times 10^4 \text{ A/cm}^2$, 0T; $J_c = 1700 \text{ A/cm}^2$ at 0.1T; YBa ₂ Cu ₃ O _{7-x} $J_c = 4 \times 10^3 \text{ A/cm}^2$	Ref. [15,190]
	Multifilamentary HTSC wires/Ag sheath	36 (Bi,Pb)SCCO filaments; 0.16 mm wire; $J_c = 1050 \text{ A/cm}^2$	Ref. [191]
Hitachi	Ag-sheathed, HTSC powders drawn and rolled into 0.5 mm tapes	YBa ₂ Cu ₃ O _{7-x} $J_c = 3.3 \times 10^3 \text{ A/cm}^2$; TBCCO- $J_c = 6 \times 10^3 \text{ A/cm}^2$; (Tl,Bi)SCCO- $J_c = 10^4 \text{ A/cm}^2$	Ref. [192,193] YBa ₂ Cu ₃ O _{7-x} result Highly oriented
NRIM	Tape cast, sintered, and rolled to high density	(Bi,Pb)SCCO; $J_c = 1850 \text{ A/cm}^2$, 0T; 30μm thick, 3 mm wide, 100 mm long	Ref. [16]
Nippon Steel	Quench-melt-growth to form monolithic conductor	YBa ₂ Cu ₃ O _{7-x} $J_c > 10^4 \text{ A/cm}^2$, 1T	Ref. [194,195] Highly oriented, dense
Mitsubishi	Aerosol particle deposition 1μm/hr onto substrate, melt textured, and annealed	BSCCO-1μm thick on (100) MgO: $J_c = 8000 \text{ A/cm}^2$, 0T, $J_c = 100 \text{ A/cm}^2$, 0.4T	Ref. [196] Oriented
NRIM	Magnetron sputtering on Hastelloy X substrate with MgO buffer layer	YBa ₂ Cu ₃ O _{7-x} - 1-2μm thick: $R = 0$ at 80K, $J_c = 200 \text{ A/cm}^2$	Ref. [197]

[†] All J_c values at 77 K.

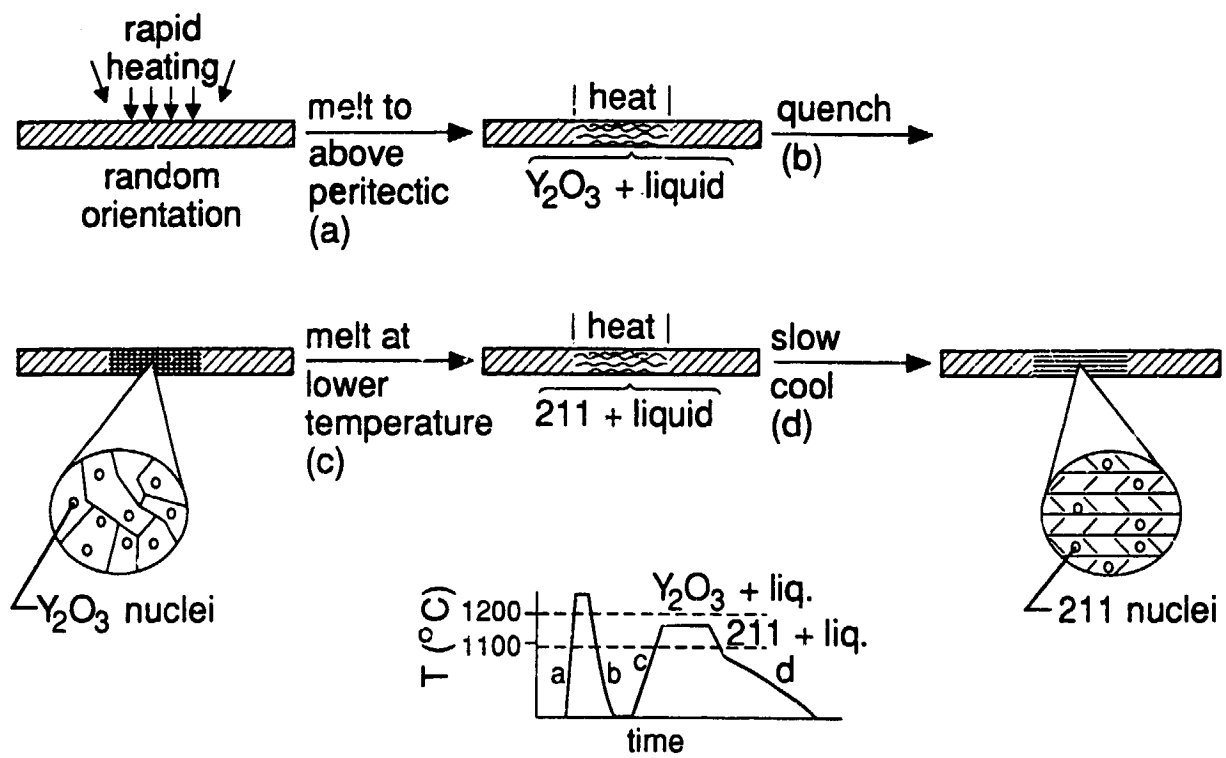


Figure 5.1: Schematic diagram outlining the steps in the quench-melt-growth (QMG) process.

air or oxygen to densify the conductor. Silver is the metal of choice because of its ductility and also due to the ability of Ag to transport oxygen to the superconductor interface. Wires produced in this fashion can then be swaged together in bundles, and reworked to form multifilamentary conductors. The wire may also be rolled down to form tape with thicknesses less than 1 mm. The mechanical work imposed on the material lends some texturing to the wire formed. Most of the published literature on this topic is by the Japanese [15,190,191,192,198].

Tapes may be prepared by classical tape-casting techniques of dispersing the high- T_c superconducting ceramic powder into an organic binder and solvent, casting the tape onto a flat surface using the "doctor blade" process to achieve a uniform slurry thickness on the order of 50 - 500 microns. The cast slurry is spread uniformly across a flat surface with a flat blade or similar device (hence the name) and allowed to dry and cure. The resulting flexible tape that can be removed from the surface on which it was formed, cut to the desired shape and processed at high temperatures to remove the organic binders and to sinter the ceramic particles. The tape at this point is in the form of a brittle ceramic. The unsintered "green" tape may also be placed onto a substrate and sintered to form a composite. Because of the plate-like morphology of the high- T_c superconducting crystallites, some texturing may result during the process as a result of the mechanical shearing that takes place during the application of the doctor blade to the slurry. There is also some propensity of the plate-like crystallites in the slurry to orient on the flat casting surface. Some or all of this grain orientation may remain after the sintering steps. Tape-casting by the doctor blade process is being investigated in Japan and in the U.S.

Another technique to draw unclad wire relies on pulling fibers from a melt. The melt may be produced by a small area laser heating of a precursor rod, and then drawing a crystalline fiber from the molten zone, using a seed crystal [181]. A somewhat analogous technique consists of drawing the fiber from a melt that has been pulled to the top of a capillary. The capillary is partially immersed in a crucible containing the melt, and continuously feeds melt to the growth zone. Texturing occurs in these processes because of thermal gradients that induce directional solidification of the fiber. There is only a small amount of work in the U.S. in this area, and none reported in Japan to our knowledge.

Other techniques that have been described in the literature such as converting alloy ribbons to the oxides [199] and spinning fibers from polymeric precursors [200] may also be amenable to producing conductors in the form of wire or cable. Transition temperatures for $YBa_2Cu_3O_{7-x}$ materials prepared by these techniques are greater than 80 K. Since critical current densities are not reported, it is too soon to judge the applicability of these techniques to conductor fabrication.

5.2.3 Processing of high- T_c Superconductors to Form Thick Films

The preparation of thick films on a substrate having the shape of a wire or tape may serve as a practical composite conductor. There are many techniques that have been described to apply thick films to substrates. These include spin-casting or dip-coating a substrate with a solution or a sol containing the metal ions, followed by conversion into the superconducting phase at high temperature. Films up to tens of microns thick may be prepared by repetitive application of the precursor coating. Highly dense films are difficult to obtain by these processes due to low ceramic yield and to the evolution of a considerable amount of gaseous byproducts from the film during decomposition of the precursor components. It is possible that subsequent melt processing could lead to higher density films. Most of the published literature in this area is from the U.S., although the area of solution processing of ceramics is a known Japanese strength.

Thick films may be deposited by spray or aerosol pyrolysis of solutions containing the metal ions onto heated substrates. Again, as the droplet or particle strikes the hot surface and precursor decomposition takes place, it is difficult to obtain dense, smooth films without resorting to post-deposition melt processing.

Plasma spraying of high- T_c superconducting oxides onto substrates has also been investigated as a technique for preparing thick films (cf., Ref. [187]). The process involves injecting the oxide powder into a plasma source and directing the resulting spray at a substrate. Very thick coatings may be obtained in this way. The plasma generated droplets are at very high temperature, and the interaction with the substrate and the rapid thermal quenching that the droplets undergo are believed to be deleterious to the coating properties because of chemical inhomogeneities and contamination from diffusion of the substrate components into the film.

Chemical vapor deposition (CVD) of volatile precursors onto substrates is another viable process for depositing both thick and thin films conformally onto non-planar substrates. The metal ion precursors must be volatile and must be stable under the conditions necessary to evaporate the precursors. The metal ion precursors are carried in an inert gas to a hot substrate where deposition and decomposition of the precursor(s) occur. The CVD process may be performed in the presence of oxygen such that the superconducting oxide phase may be grown in situ. The Japanese have invested considerable effort in this technique, and are leading the U.S. in this area. Interestingly, many U.S. researchers working in the semiconductor industry began doing high- T_c superconducting CVD research very early on, but found progress to be slow and

difficult, and consequently left the area. Now, many of these U.S. researchers are returning to the use of CVD for the preparation of high- T_c superconducting coatings because of the apparent success the Japanese have had [19,201]. Also, the availability of a variety of volatile precursors for MOCVD has prompted fresh attempts at depositing films of high- T_c superconducting materials onto substrates [202,203,204,205].

Numerous other methods of preparing thick films of high- T_c superconducting materials have been described such as screen printing [188], deposition of colloidal suspensions onto substrates [206], deposition of molten alloys that are subsequently oxidized to the high- T_c superconducting phase [207], just to name a few. Another technique having the potential to deposit uniform thick coatings in a continuous process is high deposition rate magnetron sputtering. However, there is little published in this area for the deposition of thick films.

All of the above techniques for depositing thick films of superconducting material onto substrates presently rely mainly on partial or complete epitaxy of the high- T_c superconducting oxide phase on the substrate to control the texture of the film. Epitaxy becomes increasingly difficult to control with increasing film thickness. There are a few reports that melt processing of the film may also lead to texturing, and may reduce the reliance upon epitaxy to produce texturing in thick films. Also, for the techniques that rely on depositing the high- T_c superconducting material onto a substrate to yield a form useful as a tape or wire, one of the critical issues is the reaction of the film with the substrate material. Such an interaction typically leads to the degradation of the electrical properties of the film.

5.3 Electrical and Magnetic Properties Measurements

A key concern when comparing the relative progress of the U.S. and Japanese efforts in high- T_c superconducting processing lies in the validity of comparing the critical current densities of materials measured by a number of different techniques using different instrumentation and often with different measurement criteria. In measuring the J_c of monolithic high temperature superconductors having cross sections on the order of 1 mm^2 , a current density of 10^4 A/cm^2 requires that a current of 100 A be passed through the sample leads and the sample itself. This places rigorous requirements on the quality of the contact between the lead and the sample, and the chemistry of the contact-superconductor interface. Heating of the sample is also of great concern in this situation. In order to minimize these problems, many measurements are performed in a pulsed mode with small duty cycles. Because the rate of flux

motion in many, if not all, of the high- T_c superconducting materials is slower than the pulse duration used in many measurements of J_c , the apparent J_c measured in the pulsed mode may be much greater (up to an order of magnitude) than those measured by d.c. methods. To make a meaningful comparison of critical current densities between materials processed by the many different techniques and the different laboratories, it is therefore imperative to specify the conditions under which the measurements were made. For this reason, there are often difficulties in comparing J_c 's appearing in the literature, because of insufficient information about the measurement technique used in obtaining the stated values of J_c .

In the U.S., the Defense Advanced Research Projects Agency (DARPA) high- T_c superconductivity program and the Department of Energy Superconducting Technologies for Electric Power Systems (STEPS) program have participated in attempts to encourage standardization of the measurement procedures, criteria and reporting of T_c and J_c values. This effort is beginning to pay off as more published accounts of U.S. high- T_c superconductivity research include the details of the measurements. It is hoped that this effort will be adopted internationally so that more valid comparisons with results in the Japanese literature may be made.

5.4 Summary of High- T_c Materials Processing Results in the U.S.

A representative survey of the results achieved in the U.S. in the area of monolithic conductors, wires and tapes, and thick films appears in Table 5.1, including the relevant references.

5.4.1 Monolithic Conductors

Critical current densities have improved over the past one to two years from $J_c = 500 \text{ A/cm}^2$ at 77 K in pressed and sintered powders up to 18000 A/cm^2 at 77 K in zero applied field, and $J_c = 4000 \text{ A/cm}^2$ at 77 K in a field of 1 T through the melt processing of sintered powder ceramics of $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$. These results for granular materials are on a par with those obtained for single crystals, but are still several orders of magnitude less than those of $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ thin films that have J_c values of 10^6 - 10^7 A/cm^2 at 77K and zero field (see Chapter 6).

5.4.2 Wires and Tapes

Although, the number of published results from the U.S. efforts in the fabrication of wires and tapes has been small, it is known that a number of companies are working in this potentially high payoff area. Many of the results are disappointing, with J_c 's on the order of those found in pressed pellets. The laser heated pedestal growth of BSCCO fibers appears promising, with J_c 's on the order of $60,000 \text{ A/cm}^2$ (pulsed) at 68 K having been achieved [181].

5.4.3 Thick Films

The preparation of thick films has been extensively examined in the U.S. A few spin-on processes have been developed, resulting in thick films having reasonably high values of J_c . A thick film spun onto a substrate from a polyester precursor exhibited a J_c of $5 \times 10^5 \text{ A/cm}^2$ at 4 K, while another thick film spun on from a solution of the metal trifluoroacetates had $J_c = 10^4 \text{ A/cm}^2$ at 77 K in zero applied field [184,185,186].

Thick films derived from spray pyrolysis have had low J_c values. A promising processing route involves spray pyrolysis of metal nitrates onto a substrate to yield a BSCCO film that was subsequently melt processed to a high density film having $J_c = 4000 \text{ A/cm}^2$ at 77 K [187].

A novel preparation of a thick film from a liquid metal-gas-solidification route to yield a $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ thick film on a substrate with $J_c = 3 \times 10^4 \text{ A/cm}^2$ at 77 K has been reported [207]. This technique is limited to the rare earth elements that form eutectics in the rare earth-barium-copper alloy system.

Although there are many reports of films generated in the U.S. by CVD, none of the published results have yet equaled the Japanese results in this area. Many of the U.S. results are from academic institutions, and while T_c values are reported, critical current densities have often not been.

5.5 Summary of High- T_c Materials Processing Results in Japan

The bulk conductor work at the Japanese laboratories we visited fell into three categories: wires, tapes, and thick films. The goal in each case was to produce a conformable structure that would conduct high current. As stated at one laboratory, their goal was to achieve 10^5 A/cm^2 in a wire configuration of $0.5\text{-}1 \text{ mm}^2$ cross sectional area by the end of this year (1989). While this goal would seem very difficult to obtain, significant advances have been made over the last year and the Japanese are confident they can maintain this momentum.

Japanese efforts in developing wires, tapes, and thick films of the superconducting oxide ceramics draw naturally on the Japanese commitment to ceramics as a technologically important class of materials. We neither saw nor heard of extensive work in precursor chemistry and solution processing of the oxides to yield ceramic powder starting materials. However, as stated above, this area is a known strength of Japanese industry.

The strength of the Japanese industry in conventional ceramics processing relative to the U.S. industry results from their long-term commitment to solid state chemistry, ceramic science and processing technology. Japanese materials scientists are well trained in solid state chemistry and they therefore understand microstructural evolution and control at an atomic level. This was evident from the presentations and discussions we had and is verified through the referenced publications. The Japanese progress toward achieving technologically useful current densities and conformability for wires and tapes through innovative processing is impressive (see Table 5.2 and references therein). We outline in this section some examples of this progress.

5.5.1 Wires and Tapes

Several Japanese laboratories, for example NRI, Sumitomo, Hitachi, Furukawa, and Kyoto University, are producing Ag-sheathed tapes by various rolling and pressing techniques. These techniques have produced the best results in terms of conformability and current densities (see Table 5.2), with J_c values as high as 4×10^3 A/cm² for YBa₂Cu₃O_{7-x} [190], $J_c > 1.7 \times 10^4$ A/cm² for (Bi,Pb)SCCO [15], and $J_c > 10^4$ A/cm² for (Tl,Bi)SCCO [193], all measured by d.c. transport at 77 K and zero applied field. Examples of extended lengths of silver sheath/YBa₂Cu₃O_{7-x} superconducting tapes are shown in Fig. 5.2 in the form of an extended wire, and in Fig. 5.3 in a magnetic test coil configuration.

Preliminary results for a silver-sheathed multifilamentary wire technique were summarized on our visit to NRI. This national laboratory has extensive experience with the multi-filamentary approach to conventional superconductor wire fabrication. In their process for fabricating high- T_c superconducting wire, oriented fibers of high T_c superconducting materials were achieved by filling a 10 mm Ag tube with (Bi,Pb)SCCO powder, which was cold rolled and drawn down to a 0.16 mm filament. The filament was cut into 36 wires 1.8 cm in length, packed into a 3 mm silver tube and cold worked into 0.16 mm wire. The resulting 36 filament wire had a measured current density of 1050 A/cm² (at 77K, 0T) [191]. A 252 filament Ag/YBa₂Cu₃O_{7-x} composite wire [198] has also been fabricated at NRI. The superconducting properties of the wire are not very good (showing broad superconducting transitions), but it is important



Figure 5.2: Photograph of silver sheath/YBa₂Cu₃O_{7-x} superconductor tape (0.5 mm width) used to develop large scale application prototype designs by Sumitomo Electric Industries, Ltd.

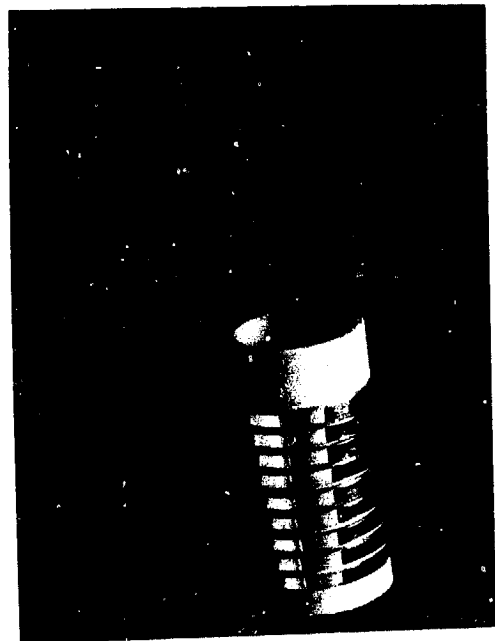
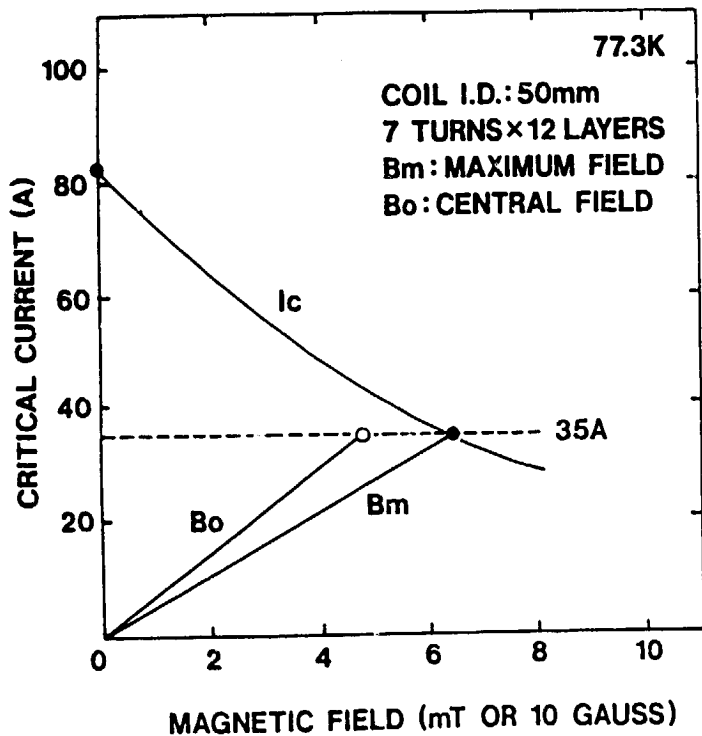


Figure 5.3: Photograph on the right shows a prototype coil made from silver sheath / $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ superconducting tape by Sumitomo Electric Industries, Ltd. The graph on the left is a plot of the critical current I_c versus maximum field through the coil.

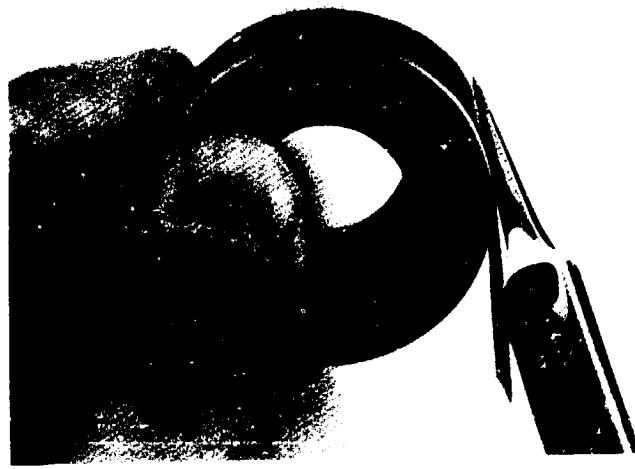


Figure 5.4: Ribbon of (Bi,Pb)-Sr-Ca-Cu-O superconductor mechanically formed on a 38 mm-diameter bobbin without fracture. Photograph provided by the National Research Institute for Metals (NRIM).

to note that the capability of multifilamentary high- T_c superconducting wire fabrication is being developed with vigor in Japan.

Researchers at NRIM are also investigating tape casting by the doctor blade process (DBP). In this so-called DBP technique, a piece of the green tape (thickness of $\sim 100\mu\text{m}$, and density of $\sim 3\text{ g/cm}^3$) was heat treated at 500°C for one hour. The ribbon was then cold-rolled to a density of 5.8 g/cm^3 . The resulting tape could be bent around a 38 mm diameter bobbin as shown in Fig. 5.4 and the best current density achieved was $\sim 2000\text{ A/cm}^2$ at 77 K and zero applied field [16].

5.5.2 Monolithic Conductors

The quench-melt-growth (QMG) process, described earlier (see §5.2.1) and having promise for wire or monolithic conductor fabrication was described by a researcher at ISTEK on a two year assignment from Nippon Steel. Critical current densities exceeding 10^4 A/cm^2 were reported in such samples at 77 K and 1 T (Ref. [194,195] and references therein).

5.5.3 Thick Films and Fibers

The Japanese are exploring two solution-derived ceramic processing techniques with an emphasis on the production of fibers and/or thick films, namely the sol-gel method and a fine particle deposition method.

The sol-gel method has been applied to solution-derived fibers of $\text{YBa}_2\text{Cu}_3\text{O}_x$.

in collaborations between Mitsubishi staff and J. D. Mackenzie of the University of California, Los Angeles [208]. Mackenzie has been involved in sol-gel processing of glasses and ceramics for several years. In this particular sol-gel process, Y, Ba and Cu ethoxides and diethylenetriamine solutions were polymerized by controlled hydrolysis. The resulting thermoplastic gel was drawn into fibers as long as 200 cm. The fibers were preheated at 250° C for one hour, then fired at 950° C for 12 hours in an O₂ atmosphere. The resulting fibers were porous (> 50% porosity) and brittle (tensile strength < 1MPa). The porosity, and thus the strength, can be controlled by altering the solution polymerization conditions. Of greater concern is the effect of organic contaminants resulting from the starting materials and solvent. Various heating schedules during and after the gelation process were attempted with limited success to date.

Another Japanese group has prepared fibers from a gel route by ion exchanging Y, Ba, and Cu ions into an alginate gel fiber. The ion exchanged fiber is then sintered to a fiber with good mechanical properties and having a T_c of 85 K [200].

Thick (30-50 mm) films of nominal composition Bi₂SrCaCu₂O_y have been deposited on MgO (100) substrates by a sol-gel process. Ethoxides of the metallic constituents in the proper stoichiometric ratios were dissolved in ethanol. This solution was dropped onto MgO substrates, pyrolyzed at 600-700° C in an O₂ atmosphere and sintered at 870° C for two hours. The resulting thick films were oriented along the *c*-axis and had a T_c of 117 K; however, no transport measurements were reported [209].

A cursory examination of the Japanese Journal of Applied Physics for 1988 indicates that a large number (> 20) of publications appeared concerning solution or colloidal processing of high- T_c superconducting materials into thick films. The critical current densities, when reported, have tended to be low (< 1000 A/cm²), as they have also been in reports from researchers in the U.S. The rate of publication on the topic of solution processing on high- T_c superconductors has slowed thus far into 1989.

The fine particle deposition method has been used to prepare YBa₂Cu₃O_{7-x} and Bi₂Sr₂Ca_{n-1}Cu_nO_x ($n = 1, 2, 3$) coatings. In this process nitrates or acetates of the metallic constituents are dissolved in water in the desired stoichiometric ratios to a total concentration of 0.2 mol/liter. A ultrasonic generator is used to produce an aerosol of the prepared solution. The mist is introduced by flowing oxygen into a reactor heated at 850°-950°C. Thus, fine particles of oxides are synthesized by thermal reaction of the aerosol and they are subsequently deposited onto an MgO (100) substrate. The substrate is annealed at 800°-1050°C for several hours in flowing oxygen to achieve the high- T_c superconducting phase. The thickness of the resulting films is about 1 μm for a one hour deposition. For the nominal composition BiSrCaCu₂O_x, a critical current

density of 8000 A/cm² was achieved below 81 K [196].

5.5.4 Magnetron Sputtered Thick Films

Scientists at the National Research Institute for Metals (NRIM) have recently reported results on YBa₂Cu₃O_{7-x} films prepared by magnetron sputtering onto a Hastelloy-X tape with an MgO buffer layer [197]. The zero resistance temperature was 80.4 K in the as-grown state and a critical current density of 200 A/cm² at 77 K and 10⁴ A/cm² at 60 K. They also reported preliminary results on YBa₂Cu₃O_{7-x} films deposited onto a bundle of Chromel fine wires which look promising with respect to physical appearance. However, no transport data were reported.

5.6 Discussion

We show in Table 5.2 representative results on wires, tapes, and thick films from selected laboratories in Japan for comparison with the U.S. results summarized in Table 5.1. As can be seen, for thick film technologies, the results to date in Japan and the U.S. are of comparable quality. However, in going beyond these benchmark results, the Japanese program has more examples of different processing technology schemes and the industrial commitment to conductor development is much greater than in the U.S. or elsewhere. The only significant U.S. effort in the technology of processing conformable, high-current conducting configurations is work sponsored by the Department of Energy, Office of Energy Storage and Distribution. This work is carried out primarily by the DOE National Laboratories in collaboration with a few industrial partners. There are a few small start-up companies, e.g., CPS Superconductor, HiT_c Superconcc, and Superconductive Components, that are working on the processing of conformal conductors with federal support, primarily supported by DARPA. However, the investment of the Japanese government and especially Japanese industry in processing technology far exceeds the U.S. in manpower, resources, and state-of-the-art equipment. The Japanese have maintained a significant effort in developing bulk superconductors with a large materials processing thrust.

5.7 General Observations

This chapter is concluded with a listing of general observations on features of the overall Japanese program in bulk superconductor processing.

- The Japanese have a positive, can-do attitude. The Japanese do not sit back and wait for a complete understanding of basic materials issues before initiating processing research and development. Instead they pursue a parallel effort that addresses the processing of ceramic oxides and composites (which are recognized Japanese strengths), while also investing resources in developing an understanding of the basic physics, chemistry and materials science of the superconducting materials and of the process itself. In a recent review mentioned earlier, the authors state "The eventual use of the new superconductors may require new processing techniques as innovative as the discovery of the material themselves" [177]. If this is the case, then the Japanese division of effort is much more suited to the task at hand as compared to that in the United States.
- The major Japanese effort focuses on silver and powder metallurgy processing with a strong emphasis on metallurgical techniques. The U.S. programs do not have a strong metallurgical processing emphasis. The Japanese effort in solution processing has declined substantially from 1988 to the present, probably in response to the lack of success in achieving high critical current density coatings with these processes. It appears that the Japanese have shifted their solution processing effort to other processing strategies.
- At all the Japanese industrial laboratories we visited there would be teams of six or more principal investigators having complementary skills and backgrounds working with technician support toward common goals. The U.S. efforts tend to be centered on individual specialists working reasonably independently, only collaborating when the occasion demands. This teamwork, that is the signature of the Japanese effort, allows for more rapid advancement when break-throughs occur.

Chapter 6

Superconducting Electronics and Thin Films

William J. Gallagher and Richard W. Ralston

6.1 Introduction

Modern superconducting electronics traces its origin back to the discovery of the Josephson effect in the early 1960's [210,211,212], and today all commercial superconducting electronics involve (low- T_c) devices based on this effect. Superconducting quantum interference device (SQUID) magnetic sensors are used in instrumentation in fundamental physics, geophysics, and biophysics [213]. For biomedical applications, there are large multichannel SQUID gradiometers under development. Furthermore, there are now commercially available sensitive ultra fast sampling oscilloscopes based on the switching of Josephson junctions, and a number of standards laboratories are now operating 1 or 10 V standards based on the a.c. Josephson effect in series strings of thousands of junctions [214].

These analog applications of Josephson devices were largely made feasible in sophisticated forms because of the development of thin film technologies for the fabrication of Josephson devices. A pioneering development of thin film technology for Josephson devices was undertaken most extensively by IBM's Research Division from just after the discovery of the Josephson effect until September 1983, when a large (> 100 person) effort to develop superconducting technology for digital computer circuits was terminated [215]. At that time, logic at the 1000-gates-per-chip level was thought to be under control, but a fully functional 4K subnanosecond random access memory (RAM) was thought to be two years away, and not to have overwhelming performance

advantage. Smaller digital Josephson research programs had also been undertaken by AT&T Bell Laboratories and by Sperry Research, but both of these programs were terminated just prior to the IBM cut-back.

Since 1980 there has been a significant effort at several Japanese laboratories aimed at developing digital Josephson technology [216]. In the last two years, these efforts have resulted in the demonstration of fully functional 4-bit-slice microprocessors with up to 24,000 junctions per chip and in memory chips of 4K-bit density that appear to be fully functional except for lithographic defects. A side result of this effort has been the development of a robust all-refractory technology that is being adopted for other applications around the world. At the present time, however, it is clear that the chip technology available in four Japanese laboratories, the Electrotechnical Laboratory, Fujitsu, Hitachi and NEC, far exceeds that available anywhere else in the world.

An additional arena of considerable promise for superconducting electronics consists of a variety of high-frequency analog signal processing devices that exploit the low microwave losses of superconductors and make use of active superconducting devices [217]. This activity has been mainly pioneered in the U.S. at MIT Lincoln Laboratory.

The advent of high temperature superconductivity offers the possibility of considerably lowering the entry threshold for these applications by enormously simplifying the cryogenics. In addition it offers the possibility of allowing superconductivity and superconducting devices to be integrated with semiconducting devices operating at a temperature at which near optimum performance can be achieved. From what is already known, most of the analog applications appear to be feasible, assuming continued progress can be made in the materials and processing aspects of the new high temperature superconductors which are complex, highly anisotropic materials. The feasibility of digital Josephson applications and the analog applications that require high quality Josephson junctions depend also on answers to certain fundamental questions about the new superconductors, such as whether or not there is a gap in the material and what is the density of excitations.

Though much work remains to be done, there has already been and continues to be considerable progress around the world in making thin films of the new superconductors that perform well in liquid nitrogen. Highly oriented films with large critical current densities have been made on selected substrates for most of the high- T_c materials systems by a number of deposition methods. Good superconducting results have been reported for patterned structures with dimensions down to less than $1 \mu\text{m}$. The basic function of r.f. and d.c. SQUIDs has been demonstrated in simple single-level grain-boundary-based devices, and impressively low noise has been reported. High frequency losses in the new superconductors at 77 K have been shown to be lower than in any cooled normal

metal. New substrate materials have been reported that will likely lead to large-area substrates with good dielectric properties.

Progress and breakthroughs are still needed however. No convincing high- T_c superconductor-insulator-superconductor junctions have been reported, nor have there been convincing liquid-nitrogen temperature demonstrations of deliberately made weak-link structures. No electrical data has been reported on multi-level structures, and, indeed, there is yet-to-be-elucidated basic physics in simple via structures between two thin-film levels of these anisotropic materials.

In this chapter we will review the low- and high- T_c electronics and thin film activities in Japan as compared to the U.S. It will become clear that Japanese capabilities in low- T_c processing and digital circuits far exceed those in the U.S. Despite inferior processing capability in the U.S., low- T_c analog circuit activity, which is much more emphasized in the U.S., is much advanced over the Japanese level. In high- T_c activities, significant contributions to advancing the state of the art in thin films have been coming from both the U.S. and Japan, but the U.S. programs have led to more interesting demonstrations of device structures.

6.2 Low- T_c Technology

6.2.1 Low- T_c Superconducting Electronics Programs in Japan

In the 1970's there were only the beginnings of superconducting electronics activities in Japan with some activity on the Josephson voltage standard and on mixers, and by the end of the decade, activity was beginning on digital circuits. In the early 1980's as part of the Agency of Industrial Sciences and Technology, Ministry of International Trade and Industry (MITI) project on high-speed computing systems for future scientific and technological uses, a coordinated program aimed at developing digital Josephson technology was undertaken at the Electrotechnical Laboratory (ETL) and at Hitachi, Fujitsu, and NEC. These efforts (involving about 10-15 researchers per laboratory) were focused mainly at chip-level technology. A separate program outside of MITI was undertaken at NTT, which was somewhat larger (about 40 people) and included a packaging interconnect component as well as materials and chip technology and circuit components. The NTT program was scaled back to a research mode shortly after the IBM decision to terminate their program, but the MITI program continued at the four laboratories throughout the 1980's and has resulted in significant refractory technology and digital circuit devel-

opments. This MITI program, however, is scheduled to end in March of 1990, and it is not clear whether or not there will be a follow-on program with a substantial digital component.

One circuit project in Japan that will clearly continue until 1991 is the five year ERATO project on the Quantum Flux Parametron, a concept invented and championed by Professor Goto of the University of Tokyo. The project was reviewed in a recent JTEC report [218], and thus only an update is offered here. The Fundamental Properties Section of the ERATO project, located in space at Hitachi's Central Research Laboratory, has recently reported low speed operation of an analog-to-digital (A/D) converter[219] and high speed (5 GHz) operation of a 3-cell pulse-counting circuit [220]. This work at present is aimed at feasibility demonstrations of circuits of not more than approximately 100 gates. The Fundamental Properties staff are focused on confirming the basic operations of quantum flux parametron circuits and on the issue of increasing operating margins (symmetry and low noise are essential to operating the parametron in its single-fluxon form). Thus, this project does not presently place emphasis on integration at the MSI-LSI level, nor does it provide the same circuit pull as the current MITI-sponsored effort. Indeed, the parametrons are fabricated in the older Nb/Pb alloy technology. Nevertheless, the long term commitment at Hitachi to this project, as a Japanese-originated exploratory research direction, seems to be firm with their stated intention to continue after the 1991 end of the ERATO project.

In April of 1988, MITI started a 10-year project on new superconducting devices with the following themes: (1) ultra high speed three-terminal devices and (2) new functional devices. The former includes research aimed at superconducting versions of field effect transistors (FETs) and superconducting base transistors, while the latter will explore and attempt to exploit mechanisms like single electron tunneling and localized state tunneling. It was apparently a hotly debated issue whether or not to include advanced Josephson circuits in this project. The decision not to include these is apparently being reviewed in the light of U.S. proposed consortia initiatives, and the ending in March 1990 of the MITI Josephson Computer Project. There also appears to be discussion and planning of a follow-on Josephson project that would include both instrumentation and data processing.

6.2.2 Integrated Thin Film Processes for Josephson Technology

The absence in Josephson technology of a three-terminal transistor-like device places a premium on controlling the characteristics of the two-terminal devices. Two-terminal devices provide little or no direct isolation between the control

signal and the controlled signal, deliver minimal power gain, and thus make it very difficult to create complex circuits. For example, sense gates in memories can create sustained disturbances of stored data, and only very careful design with nearly ideal components can produce functioning memories. To implement such designs requires tight control of signals and of component characteristics. It must also be borne in mind that the key element of the Josephson junction is a tunnel barrier of thickness 10-20 Å, whose thickness exponentially determines the maximum magnitude of the Josephson current. For these reasons extreme process control is vital for producing functional Josephson circuitry.

By 1980 when digital Josephson research had begun in Japan, there had already been much published work on Pb-alloy based junction technology for integrated circuits, and work on technologies based on Nb/Nb-oxide/Pb-alloy and Nb/Nb-oxide/Nb junctions was just beginning to be reported. Most of the early circuit work had been done at IBM where the Pb-alloy based technology was developed [221]. In addition, some circuit work had been done at AT&T Bell Laboratories, using Pb-alloy based technology, and all-Nb technology explorations took place at IBM-Zurich [222], Sperry Research [223], and AT&T [224]. The early Japanese circuit work at the Electrotechnical Laboratory (ETL), NTT, Fujitsu, NEC, and Hitachi utilized Pb-alloy circuitry.

Throughout the 1980's, extensive investigations of alternative all-refractory junction technologies were carried out at ETL. By the mid 1980's there were several successes with demonstrations at ETL of the bases for LSI level refractory technologies employing three different junction technologies: Nb/Al-oxide/Nb [225], NbN/Nb-oxide/NbN [226], and NbN/MgO/NbN [227] junctions. The original demonstration of high quality Nb/Al-oxide/Nb junctions was carried out by M. Gurvitch and co-workers at AT&T Bell [224], but the NbN junction work as well as the integrated process development was pioneered at ETL [226,227]. Each of these junction technologies has been successfully used to make LSI-level digital circuitry at ETL. Among these, however, the junction characteristics of the Nb/Al-oxide/Nb technology are the most nearly ideal, and the processing for Nb is somewhat simpler than that for NbN.

After its development at ETL, the Nb/Al-oxide/Nb technology was quickly acquired by the Japanese companies in the MITI-sponsored Josephson Scientific Computing System project: Fujitsu, NEC, and Hitachi. Each company now practices this technology at the LSI-level as can be seen in Table 6.1. Typically the transfer was accomplished very efficiently by having a researcher from the industrial company work at ETL for several months to become "steeped" in the technology before bringing it back to his home firm. The perceived excellence of this technology, particularly compared to the Pb-alloy technologies that it replaced, was undoubtedly as big a factor in this successful technology transfer as was the joint research and development framework of the MITI Josephson

Table 6.1: Low- T_c Josephson Technology in Japan

Institution	Application Focus	Junction	Lithography	Chip Density	Wiring Material	References
Fujitsu	Microprocessor	Nb/Al ₂ O ₃ /Nb	1.5 μ m jnts 2.0 μ m wire	3,056 gates (24,000 jnts)	Nb	[228]
	SQUID with integral feedback	Nb/Al ₂ O ₃ /Nb	---	4 jnts	Nb	[229]
	RAM DRO	Nb/Al ₂ O ₃ /Nb	2.5 μ m	4 k bit	Nb	[230]
Hitachi	Microprocessor	Nb/Al ₂ O ₃ /Nb	5 μ m jnts 2.5 μ m wire	2,066 gates	Nb	[231]
Goto/Hitachi	Quantum Flux Parametron	NbN/NbO _x /Pb alloy	5 μ m jnts	4 parametrons + 4 SQUIDs	Pb alloy	[232]
NEC	RAM	Nb/Al ₂ O ₃ /Nb	4 μ m	1 k bit	Nb	[233]
ETL	Multi Chip					
	Microprocessor					
	- Arithmetic logic	Nb/Al ₂ O ₃ /Nb	3.0 μ m	1273 gates	Nb	[234]
	- Control Unit	NbN/MgO/NbN	2.5 μ m	593 gates	Nb	[235]
	- Instruction ROM	NbN/MgO/NbN	3 μ m	1280 cells + 789 gates	Nb	[236]
	- RAM	Nb/Al ₂ O ₃ /Nb	3 μ m	1 K cells + 1025 gates	Pb alloy	[237, 238]
	Voltage Standard	Nb/Al ₂ O ₃ /Nb	25 x 40 μ m ²	2400 jnts	---	[239]
SQUID Gradiometer	Nb/Al ₂ O ₃ /Nb	3.5 μ m	---	Pb alloy	[240]	
10 K SQUID	NbN/MgO/NbN	~ 5 μ m	2 jnts/8 x 8 μ m	NbN	[241]	

Table 6.2: Low- T_c Josephson Technology in the U.S.[†]

Institution	Application Focus	Materials	Lithography	Circuit Density	Wiring
U.C. Berkeley	Decoder, A/D converter shift register, SQUID	Nb/Al ₂ O ₃ /Nb	2-4 μm	50 gates/chip	Nb
Cornell U.	THz receiver with local oscillator	Nb/MgO/NbN	0.25-1 μm	2 jncts./chip	Nb, NbN
HP	A/D converter	Nb/Al ₂ O ₃ /Nb	2 μm		Nb
Hughes	A/D converter	NbN/MgO/NbN	3 μm	100-200 jncts./chip	NbN
HYPRES	sampler, A/D converter, SQUID	Nb/Al ₂ O ₃ /Nb NbN/MgO/NbN	2.5 μm	30 jncts./chip 100cts./chip	Nb
IBM	SQUID	Nb/Nb ₂ O ₃ /PbAuln edge jncts.	2.5 μm	~ 64 SQUIDs/chip	PbAuln
JPL	Mixers	NbN/MgO/NbN	1 μm	2000 jncts./chip	NbN
NIST	voltage standards, SQUID, A/D converter, fast counter	Nb/Al ₂ O ₃ /Nb	2 μm	19,000 jncts./chip	PbAuln
Lincoln	integrating correlator	Nb/Nb ₂ O ₃ /Pb	5 μm	1000 jncts./chip	Pb, Nb
SUNY Stony Brook	Microwave/sub mm source with mixer	Nb/Al ₂ O ₃ /Nb	1 μm	40 jncts./chip	Nb
TRW	A/D converter	Nb/Al ₂ O ₃ /Nb	2/4 μm	50/100 gates/ chip	Nb
Univ. of Utah	SQUID, receiver, comparator, oscillator	NbN/MgO/NbN	2 μm	16/chip	NbN
Westinghouse	shift register	Nb/Al ₂ O ₃ /Nb	2/5 μm	50 jncts./chip	Nb
U. of Wisconsin	Microwave amplifiers, oscillators	Nb/Nb-oxide/Pb NbN/MgO/NbN	2 μm	5 devices/chip	Pb, NbN

[†] Entries are based on a telephone survey of current research work.

Computer project. The Nb/Al-oxide/Nb technology is now also practiced at lower scales of integration at other laboratories throughout Japan (in universities and in companies with smaller efforts, as for example, a SQUID-sensor effort at Mitsubishi). Furthermore, its use is becoming widespread in the U.S. (for example, at Hypres[242]) and in Europe as well, though typically at lower levels of integration, as can be seen in Table 6.2. ETL has hosted a number of overseas visitors who have worked with the Josephson technology group. The transfer of their technology to the world seems to be in keeping with ETL's goal of being a world-class research laboratory.

An additional thrust of the ETL process development work was to replace Pb-alloy wiring with refractory (Nb or NbN) wiring on the upper levels of Josephson integrated circuits, and in particular to develop processes that resulted in flat ("planarized") surfaces at the upper levels [226]. This was needed to improve the yield of upper level wiring against interlevel shorts and line breaks, but was also thought to lay the basis for eventual stacking of Josephson circuits in what might become three-dimensional integrated technology. (There has also been a MITI thrust at developing three-dimensional integrated technology.) Some of the planarization effort has been picked up at the companies [243], but its impact appears to be less pervasive. For circuit demonstrations,

Table 6.3: Selected examples of Nb/Al₂O₃/Nb digital integrated circuit developments at Fujitsu.

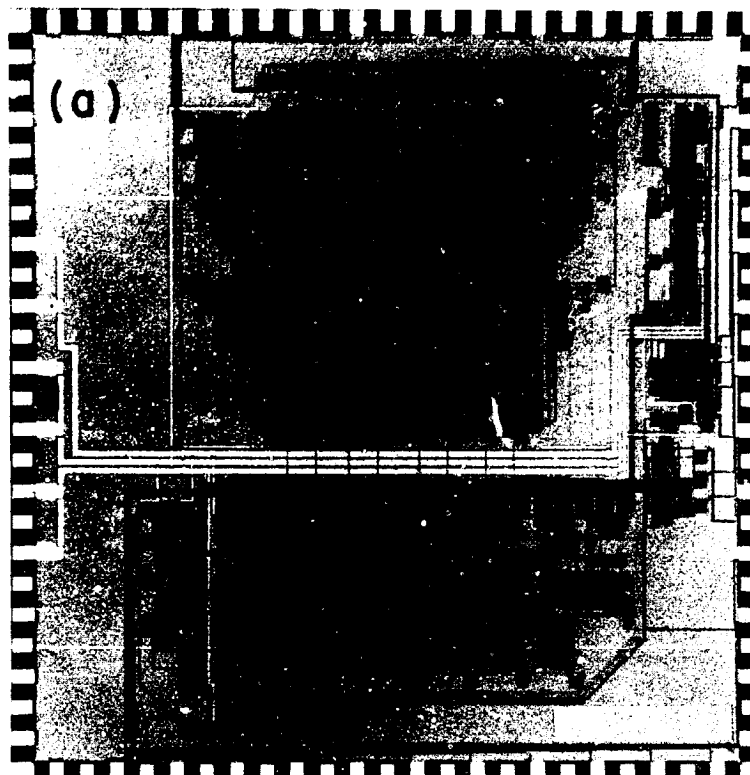
Year	Circuit	Speed	No. Gates	Junction Diameter	References
1986	16 bit multiplier critical path model	1.1 ns	828	2.5 μm	[244]
1987	4 bit microprocessor	770 MHz	1841	2.5 μm	[245]
1987	16 bit arithmetic logic unit	860 ps	900	2.5 μm	[246]
1988	4 kbit static memory (destructive readout, random access)	590 ps	4k-bit	2.5 μm	[230]
1989	4 bit microprocessor + 4 bit multiplier + 12 bit accumulator + 8 kbit memory read-only	1.1 GHz	3056	1.5 μm	[228]

the use of Pb-alloy interconnection was in some cases described as being more expedient than using the refractory planarization processes involve. Beyond demonstrations of one junction stacked on a second, there does not appear to have been much effort devoted to functional three-dimensional Josephson integrated circuits.

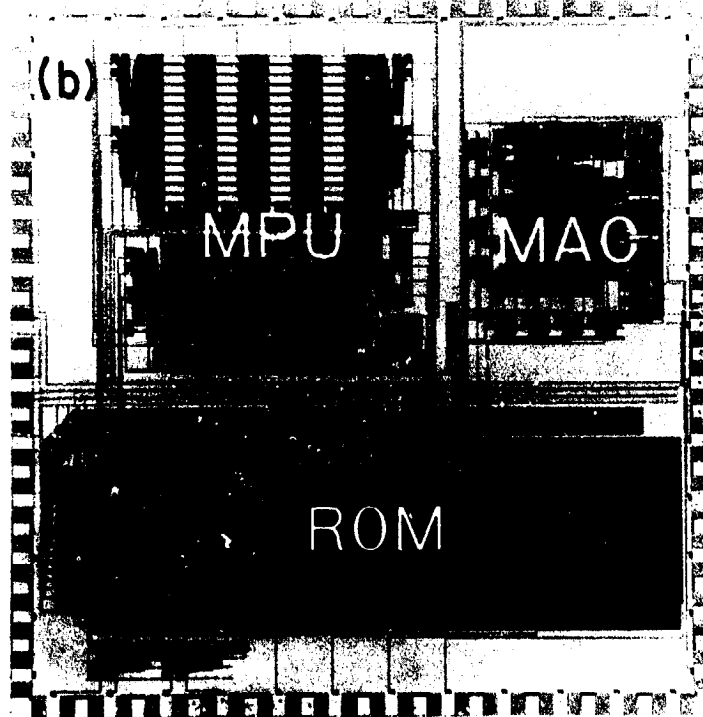
6.2.3 Digital Circuits – A Japanese Domain

Since the nearly simultaneous terminations of the IBM, AT&T, and Sperry digital Josephson efforts in 1983, there has been virtual no digital Josephson R&D in the U.S. In Japan, there has been substantial progress in logic circuitry beyond IBM's 1983 level of 1000 gates-per-chip. There has also been progress in Josephson circuits and memories, but when measured against the 1983 IBM projection of a subnanosecond 4K bit memory chip by 1985, and when measured against semiconductor performance, these results have been less impressive.

The pace in Josephson circuitry over the past few years has been set by the group at Fujitsu. Table 6.3 summarizes the circuits they have reported, all using Nb/Al₂O₃/Nb-junction technology. The first Josephson microprocessor, reported at the International Solid-State Circuits Conference (ISSCC) in early 1988, attracted the most attention [245]. This microprocessor, pictured in Fig. 6.1(a), was functionally similar to the 4-bit AM-2901 silicon microprocessor manufactured by Advanced Micro Device Inc.[247]. It had a total of 1841 gates, 48 bits of random access memory, and a few registers on a 5-mm by 5-mm



(a) Josephson 4b Microprocessor



(b) Josephson 4bit Processor

Figure 6.1: Fujitsu microprocessor chips made (a) in 1988 [245] and (b) in 1989 [228] (see text).

chip. All functions in the microprocessor were verified to work with a pattern generator running at 100 MHz. Pulse generators were used to verify that the 41-gate critical path operated up to 770 MHz. Individual gates in the critical path were working with an average of 10-12 ps delays, with a 50% duty cycle and some propagation delay comprising the remainder of the 1.3-ns cycle time. The Fujitsu Josephson group compared their cycle time to the 72-MHz clock rate of a GaAs version (enhancement/depletion process) of the same chip [248]. A somewhat less favorable point of comparison would be to a 128-MHz, 32-bit GaAs heterojunction-bipolar-transistor (HBT) reduced-instruction-set (RISC) microprocessor [249]. This chip, reported by Texas Instruments at the 1988 International Solid-State Circuits Conference (ISSCC), contained more than 12,000 gates and had a critical path length of 30 gate delays.

In May 1989 at the VLSI Symposium in Taiwan, Fujitsu reported[228] on an extension of their 1988 Josephson microprocessor in which the 1988 microprocessor was shrunk to about a quarter of its earlier size and combined with multiplier circuitry and 8K bits of read-only memory (ROM) on a 5-mm by 5-mm chip, see Fig. 6.1(b). The evolution from the 1988 chip to the 1989 chip was quite substantial. The clock frequency increased from 770 MHz to 1.1 GHz. The technology evolved from 2.5- μm minimum feature sizes to 1.5 μm , and the number of Josephson junctions increased from 5,011 to 24,000. In addition to the microprocessor core which has a 8-function arithmetic logic unit (ALU) and a 64-bit RAM, the chip also had a 256 by 32-bit instruction/data ROM, a 4-bit by 4-bit multiplier, a 12-bit accumulator, and a sequencer.

The Fujitsu group has recently completed the design of a 10,000 gate microprocessor chip which is to include 4K bits of random-access memory, a more flexible sequencer, and, presumably, the 16-bit arithmetic logic unit and multipliers that they earlier demonstrated. They expect to complete the fabrication and test of this version in 1989.

The other Japanese Josephson groups are also working on microprocessors. Hitachi[231] at the 1989 ISSCC reported a microprocessor of complexity and performance comparable to the 1988 Fujitsu microprocessor. ETL has reported experimental results on the four chips that comprise its targeted microcomputer system: an address control unit[235], an instruction memory[236], an arithmetic logic unit[234], and data memory[237,238].

The progress in memory technology has been less impressive. It can be seen in Table 6.1 that ETL, Fujitsu, and NEC have all reported experimental results on Josephson RAM chips. None of the chips reported was fully functional. However, the functionality of each component type in the chips was demonstrated, and lithographic defects contributed to the lack of full functionality. The Fujitsu and NEC results included access time measurements, with a reported minimum access time of 590 ps for the 4K bit Fujitsu destructive-

readout chip, and 570 ps for the NEC 1K bit nondestructive-readout RAM. ETL estimated a 500-ps access time from measurements of the component delays involved in an access for their destructive readout memory. Both the Fujitsu and ETL memories compensated for the destructive readout with circuits that automatically rewrote the data after readout. The Fujitsu, NEC, and ETL chips dissipated 19, 13 and 1.9 mW, respectively.

These access times, while impressive, are comparable to those now being reported in comparable density high speed semiconductor memory. For instance, in 1986, 1.0-ns access times were achieved in a 5K-bit static random access memory (SRAM) in silicon bipolar-transistor technology [250], and by 1988 this had evolved to a 0.85 ns access time in a similar silicon bipolar RAM [250,251]. Half nanosecond access times were demonstrated in a room-temperature 1K by 4-bit GaAs high electron mobility transistor (HEMT) SRAM in 1987 [252]. In contrast to the situation with semiconductors, there is no clear approach to achieving high speed Josephson memories with densities beyond 4-8K bits/chip. Without an appropriate memory technology, a general-purpose computer system cannot take full advantage of the high-speed, low-power Josephson junction logic.

For this reason, it is not at all clear whether low- T_c electronics will be commercialized in Japan, at least in the digital form which has been the thrust of the effort that MITI partially funded. There is no evidence of any imminent commercialization because, for instance, there appears to be no effort in Japan presently directed at system level issues such as multichip interconnection and cryogenic packaging. Dr. Kawabe, Chief Researcher of Hitachi Central Research's Second Department and Director of Hitachi's recently formed Superconductive Electronics Center was more optimistic than NEC or Fujitsu management about the future of low- T_c digital circuits. He envisioned at least a portion of a future-generation supercomputer as being superconducting. He argued that silicon and gallium-arsenide-based devices would ultimately reach their scaling limits, and R&D in superconducting digital electronics should be continued in order to prepare for that opportunity. Fujitsu and NEC are less certain, and this difference may be a result of their research for "the day after tomorrow" objectives, as opposed to Hitachi's research for "ten years out." Dr. K. Kurokawa, Manager of Fujitsu's Atsugi Laboratory, was sympathetic to his researchers' desires to continue low- T_c circuit development, but appeared likely to reduce the activity upon the cessation of MITI funding. The Fujitsu low- T_c team, which was quite open with the JTEC panelists regarding future plans, had already been reduced in numbers in order to provide researchers for high- T_c efforts. The Fujitsu team was clearly concerned about the stability of their low- T_c activity. NEC's low- T_c memory effort already appears to be at least temporarily scaled back.

6.2.4 Low- T_c Analog Devices and Circuits - A U.S. Domain

In contrast to the situation with digital Josephson electronics, the U.S. has remained strong in analog Josephson electronics and maintains a leadership position. This continues to be the case, although the leadership is threatened by the ready availability of superior thin film technology in Japan and the increasing analog device sophistication of Japanese superconducting electronics researchers.

All of the U.S. activity in low- T_c electronics, listed in Table 6.2, is seen to be focused on analog applications. The activities are spread among a fair number of institutions and the driving factors come from diverse, longer term commercial, scientific, and defense interests. The development foci include: ultra-sensitive scientific and biomedical instrumentation; low-noise, high-frequency receiver front ends and wideband signal processing; more reliable and practical voltage standards; sensitive, fast sampling oscilloscopes and transient recorders; and fast, accurate analog-to-digital (A/D) converters.

The high-frequency applications are principally driven by DoD receiver applications, although radio astronomy applications are also a driving force for receiver development. The DoD-directed work includes the high frequency Josephson sources research at SUNY Stony-Brook, parametric amplifier research at TRW, integrating correlator work at MIT-Lincoln Laboratory, the A/D converter work which has been carried out at U.C. Berkeley, TRW, NIST, and other U.S. laboratories, and passive analog signal processing involving filters and resonators made from low-loss superconducting transmission lines, which has been pioneered at MIT's Lincoln Laboratory. This activity, as well as the Hypres effort to develop a general purpose high-speed sampling oscilloscope for the commercial market, remains almost an exclusively U.S. undertaking.

Research on SQUIDs, voltage standards, and the superconductor-insulator-superconductor (SIS) mixers are all carried out internationally, with U.S. researchers generally leading the way. In SQUID instrumentation, the U.S. has consistently led both in laboratory innovations and in commercial products. However, the commercial U.S. product technology, which is a hybrid of a thin film sensor and a wire wound coupling structure, has considerably lagged the thin film devices made and used in laboratories like those at IBM, U.C. Berkeley, and NIST. Continued U.S. product leadership in these areas is threatened as the Japanese-developed refractory thin film technology becomes readily available throughout the world and the device sophistication of the Japanese themselves increases. This is true for both the lowest noise instruments, as well as for more specialized niches. ETL in conjunction with the Chiba Institute of Technology, for instance, has demonstrated respectable operation of an all NbN

SQUID at 10 K [241]. The commercial market place, with recent growth in demand for magnetic susceptometers and looming large scale biomagnetic instrumentation, is also become more active internationally. The Japanese Hoxan Company is now delivering susceptometers in Japan, statedly in response to poor service support for U.S. products in Japan. In addition, the Siemens corporation has recently described a 30-channel biomagnetic instrument [253] with advanced thin film SQUIDs made using Nb/Al-oxide/Nb technology. This instrument is apparently a product preprototype.

Over the last decade, led by a series of experiments done both independently and jointly among researchers at NIST in the U.S. and the PTB in West Germany, the voltage of practical Josephson standards has been raised from 5mV to 1 V [254,255], and very recently to 10 V [256]. These developments depended on deepened understanding of the physics of r.f.-driven Josephson junctions, on careful microwave engineering, and on fabrication of large, uniform arrays of Josephson junctions. This combination of skills residing at the NIST laboratory in Boulder have allowed them to lead in this activity. NIST demonstrated the first 1-V Josephson standard, and is the only standards laboratory to have made and operated 10-V Josephson standards. Furthermore NIST has fabricated chips for and aided the establishment of series array voltage standards operating at approximately 20 government and industrial standards laboratories, with four operating systems being the 10-V standard. Commercial products based on this development are possible, but U.S. leadership is clearly threatened by the availability of superior thin film Josephson technology in Japan. Researchers at ETL have already successfully fabricated and demonstrated a 1-V standard [239].

The discovery of high temperature superconductivity has substantially raised the visibility and offers to increase the practicality of small scale superconducting analog components and circuits. This creates a potential advantage for U.S. device experts to lead the way in exploiting the new materials. At this time it does appear that U.S. (and European) high- T_c device demonstrations have been more impressive, as discussed in the next sections of this chapter. The present U.S. advantage is precarious, however, if superior low- T_c technology remains the norm in Japan, and if the analog device expertise there grows in conjunction with overall Japanese superconducting film and electronics developments.

6.3 High- T_c Technology

6.3.1 Introduction

The potential electronic circuit applications of high- T_c superconductors will require first that these materials be available in thin-film form and further that the substrates, superconducting films, and associated normal metal and dielectric films be amenable to processing by methods of not much greater cost or complexity than those practiced in semiconductor and low- T_c integrated circuit technologies. The chemical complexity of the high- T_c materials is on a level with the most difficult compound semiconductor technologies and it is expected that a long and arduous development will be required to achieve multi-level high- T_c superconducting integrated circuits. Single level devices which rely on low microwave losses such as simple interconnects, microwave filters, etc. may be realized within the next few years. More intricate applications will require substantial time for the development of multi-level technologies, especially the reproducible engineering of Josephson devices.

Overall it appears that contributions to the development of high- T_c films and electronics, described in the rest of this chapter, have been coming at a roughly equal pace in Japan and the U.S. This can be seen in our attempt in Table 6.4 to list some of the highlight "first" accomplishments in superconducting films since the discovery of high temperature superconductivity.

Some differences in emphasis can however be detected in the two countries. A number of the Japanese film accomplishments (for instance, high J_c in three films systems and successful chemical vapor deposition (CVD) and layer-by-layer sputter deposition) seem to reflect a greater emphasis on the meticulous persistence it takes to optimize processes that are at first difficult to bring under control. On the other hand, a number of the U.S. accomplishments relating to prototype devices reflect a closer coupling between device and materials research, and the greater U.S. experience in analog applications of (low- T_c) superconducting films. In the following sections we describe in more detail some of the high- T_c film and device activity in Japan and the U.S.

There are also what might be termed "cultural" differences between the industrial high- T_c film and electronics research in the two countries. Besides the largest integrated electronics manufacturers who are active in both countries, in Japan there is much greater activity in medium-sized electronics companies, e.g., OKI, Sanyo, Sharp, Sony, and Sumitomo Electric. On the other hand, the U.S. has very small specialized start-up companies, e.g., BTI, Hypres, Conductus, Superconductor Technology Inc. (STI), for which there is no Japanese counterpart.

Table 6.4: High- T_c superconducting thin film and device highlights.

Achievement	Organization	Date [†]	Reference
First high- J_c film at 77K (YBaCuO)	IBM	5/87	[257]
First $J_c > 10^6$ A/cm ² at 77K (YBaCuO)	NTT	7/87	[17]
First <i>in-situ</i> growth (YBaCuO)	Cornell	8/87	[258]
First ultra-thin (100 Å) film (YBaCuO, $T_c = 82$ K)	Kyoto Univ.	6/88	[18]
First high- J_c <i>in-situ</i> laser- deposited film	Bellcore	6/88	[20,259]
High J_c in all high- T_c film materials (Tl...,Bi...,Y...)	Sumitomo	7/88	[260]
New perovskite substrates (LaGaO ₃ , LaAlO ₃)	IBM & TRW	9/88	[261,262]
Synthesis of $n = 3, 4, 5$ BiSrCaCuO films	Matsushita	9/88	[263,264]
First low noise SQUID (Tl...)	IBM	11/88	[265,266,267]
First high- J_c CVD film	Tohoku Univ.	11/88	[19]
Film with low microwave losses (36 GHz, 77K)	Siemens & Wuppertal	11/88	[268]
First high- J_c film at 77 K on silicon with buffer layer	Bellcore & NEC	12/88	[269]
Picosecond pulse propagation	AT&T	3/89	[270]
First two-level high- T_c device (microstrip resonator)	Stanford Univ. & HP	4/89	[271]
High- Q coplanar transmission line resonator (Q 14× higher than for Cu at 9 GHz, 77K)	Siemens & Tech. U. of Munich	5/89	[272]

[†] Paper submission date

Table 6.5: Thin film $\text{ReBa}_2\text{Cu}_3\text{O}_7$ critical current density achievements at 77K.

J_c (A/cm ²)	Organization	Date [†]	Reference
1.0×10^5	IBM	5/87	[257]
1.8×10^6	NTT	6/87	[17]
2.5×10^6	Sunitomo Electric	2/88	[273]
4×10^6	U. of Kyoto	6/88	[18]
4.5×10^6	Bellcore-Rutgers	8/88	[20]
5.5×10^6	Karlsruhe	11/88	[274]

[†] Paper submission date.

6.3.2 High- T_c Thin Films

By many measures, thin film high- T_c materials research in Japan is on par with that in the U.S., and the activity in these two countries appears to be leading the world. Table 6.4 includes about half a dozen highlight accomplishments relating to film growth from each of these two countries. Lists such as those in Table 6.4 are subjective and inevitably emphasize highly visible accomplishments, and may tend to underemphasize influential, sustained, systematic work that necessarily takes a longer time to complete and report. Nevertheless, this list which tries to report significant milestones in superconducting films and devices at 77 K will serve our purpose of providing one comparison point of work between the two countries.

Early thin film accomplishments relate to simply learning to grow high quality films, with an early measure of film quality being maximum critical current density. Because of the large anisotropy of the high- T_c superconductors and their unfavorable grain boundary properties, high current density appears to largely reflect the degree of single crystallinity and orientational alignment in these materials. Table 6.5 lists, to the best of our knowledge, current density records in $\text{ReBa}_2\text{Cu}_3\text{O}_7$ films and the table shows, as did Table 6.4, that significant steps were first taken in Japan and the U.S., with the present record of 5.5×10^6 A/cm² first being reported from Europe, by the Kernforschungszentrum in Karlsruhe, FDR [274]. (A number of laboratories have now reported films with comparable supercurrent densities.)

A more sensitive gauge of the quality of film growth might be gleaned from the ability to grow ultra-thin films. To illustrate this point, we present in Fig. 6.2 the resistive transition of a number of sub-100-Å $\text{YBa}_2\text{Cu}_3\text{O}_7$ films on SrTiO_3 substrates. Figure 6.2(a) shows that zero resistance was achieved

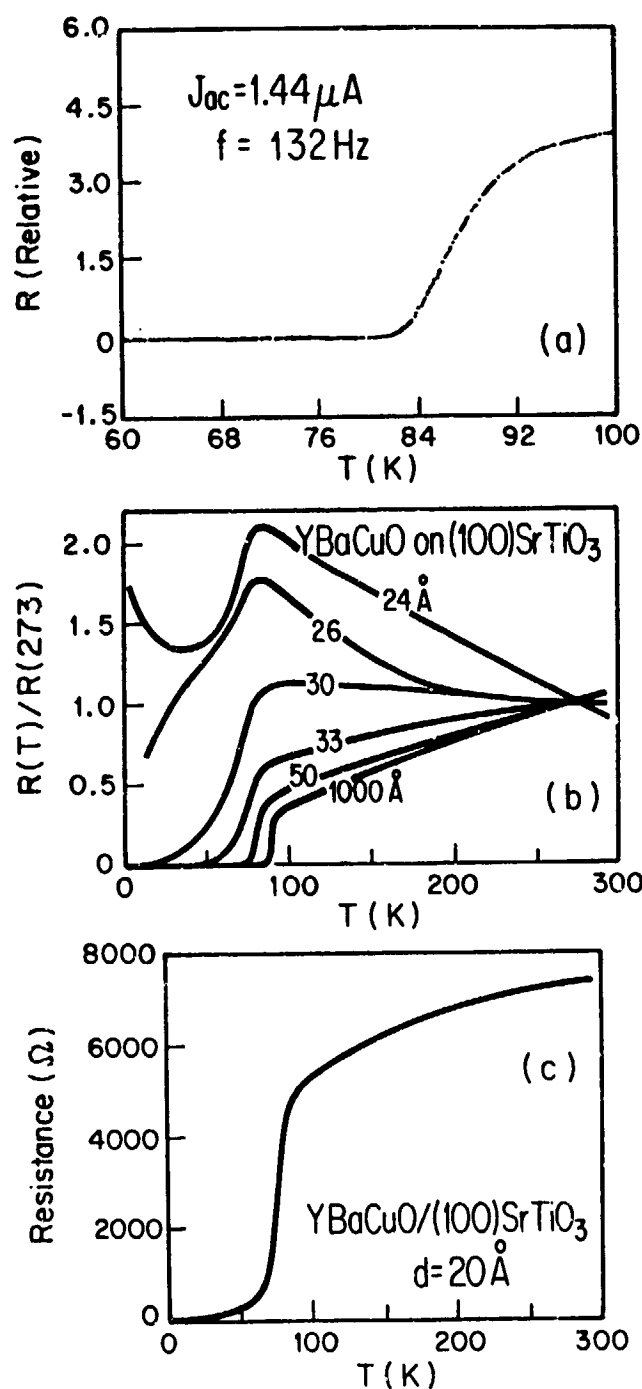


Figure 6.2: (a) Relative resistivity versus temperature for an oxidation treated (001) YBaCuO ultra-thin film (100Å) grown by electron beam evaporation in an oxygen plasma [18].
 (b) Normalized resistance $R(T)/R(273)$ versus temperature for YBaCuO films of different thicknesses on (100) SrTiO₃ substrates. The accuracy of the thickness determination of the ultrathin films is about 10% [275].
 (c) Transition curve of resistance versus temperature for an exceptionally good 2-nm thick YBaCuO film on (100) SrTiO₃ [275].

at 82 K for a 100 Å film crystallized as grown *in situ* in an e-beam deposition chamber with an active oxygen source at the University of Kyoto [18]. Figure 6.2(b) shows examples of even thinner films grown with inverted cylindrical magnetron sputtering equipment at Karlsruhe [275]. Finally, Fig. 6.2(c) shows a 20Å Karlsruhe film, approximatedly two unit cells of YBaCuO thick, with a substantial portion of a superconducting transition occurring above 60 K. That these ultra-thin growth accomplishments first occurred by e-beam and sputtering in the countries in which they did is a curious story that illustrates the value of sustained research in a given specialty. E-beam deposition of YBaCuO has been a much more widely practiced method in the U.S., with earlier noteworthy achievements coming from IBM [257], Stanford University [276], Cornell University [258], AT&T Bell Laboratories [277], and the University of Texas [278], for example. However, it turns out that the group at Kyoto University led by Professor Bando has been engaged in the epitaxial growth of oxide and selenide films by reactive evaporation for many years, including work on artificial superlattices of magnetic materials like CoO and NiO [279]. Single source sputtering, on the other hand, is a deposition technique which has been overwhelmingly emphasized in Japan. For example, the group at Sumitomo, using sputtering, was the first to produce films with J_c above 10^6 A/cm² for all of the materials systems with transition temperatures above 77 K [260]: YBaCuO, BiSrCaCuO, and TlBaCaCuO. However, the Karlsruhe group led by Dr. J. Geerk, is expert in both sputtering and surface characterization, and designs and builds unique, sophisticated cylindrical magnetron sputtering guns, allowing them to produce very thin films of high quality.

One often-considered question is which method of film growth is "best." It turns out that many methods, practiced by expert research groups, have been made to work very well, as the above examples illustrate. Overall, however, there has been greater emphasis on pulsed laser deposition and multi-source evaporation and sputtering in the U.S. and greater emphasis on single-source sputtering and CVD in Japan. It is interesting to note that sputtering and CVD are generally regarded as processes more suited for scale-up and manufacturing, while multi-source deposition and pulsed laser deposition are more flexible processes, especially useful for doing research on relatively smaller area samples. CVD is the one method that has lagged in yielding high quality superconducting materials. But recent results at several Japanese laboratories indicate that persistence with the CVD method is paying off. Both Tohoku University [19] and OKI [280] have now reported films by CVD with current densities in the 10^6 A/cm² range. Figure 6.3, reproduced from an OKI report at a device and film international workshop, shows the trends in producing high current density films, and how by this measure of film quality, CVD films are now approaching critical current density levels of physically deposited films.

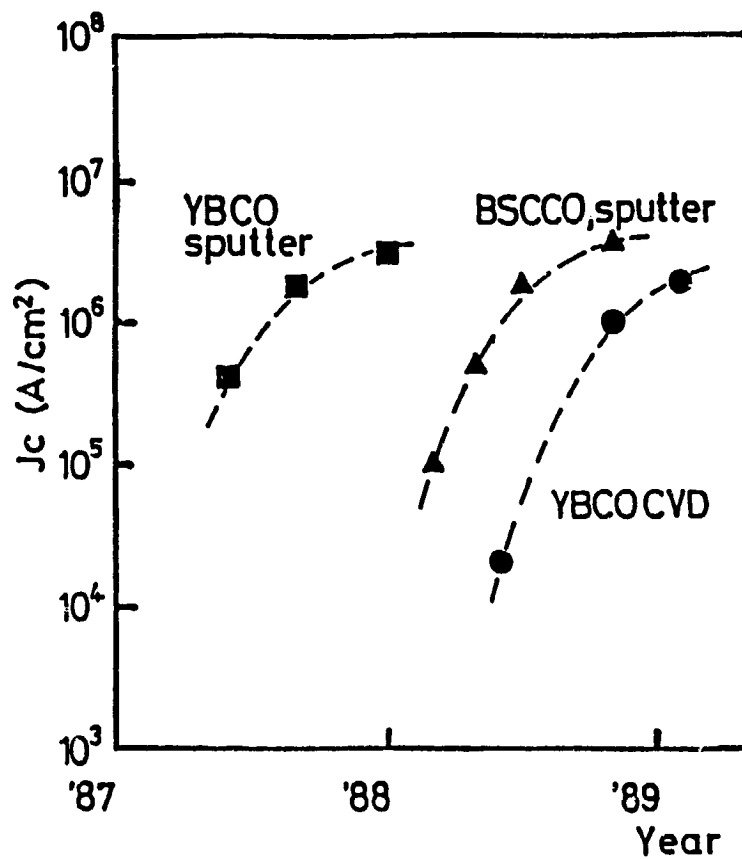


Figure 6.3: Improvements in critical current densities J_c of high- T_c superconducting thin films over time by different processing methods and materials. The ticks on the time axis denote the beginning of each year [280].

Layer-by-layer epitaxy may be an even more elusive long term film growth technique. There are in both the U.S. and Japan the beginnings of such efforts, which necessarily have a longer incubation period because of the complexity of the equipment involved and the uniqueness of high- T_c oxide materials in this context. The only concrete results with this approach appear to be the successful layer-by-layer synthesis of the 3, 4, and 5 CuO layer-per-unit-cell BiSrCaCuO compounds at Matsushita using, not MBE-like equipment, but a rotating aperture moving over four sputtering targets [263,264].

The patterning of films appears to be on a roughly equal footing in the two countries. NEC's fabrication by focused ion beam etching of a 0.8- μm -wide by 2mm-long line of magnetron-sputtered YBaCuO on MgO with a zero resistance transition temperature of 78 K is probably the longest fine line superconductor yet produced [281], but comparably fine feature sizes are being achieved at a number of U.S. laboratories. In both countries there are now only the beginnings of the selective etching and multi-level deposition processes that will eventually be needed for complete device fabrication.

An important issue for high- T_c microelectronics applications is that of the substrates used for thin films. It does not appear that research and development of substrates is as intense in Japan as in the U.S. Little or no effort on new substrate materials such as LaGaO₃[261] or LaAlO₃[262] was discerned during our visits to Japanese laboratories, in contrast to the very active state of substrate research in the U.S. One example, however, of novel "substrate" work in Japan involved CVD buffer layers on silicon which is an outgrowth of earlier Japanese research on approaches to silicon-on-insulator technology and piezo-electric devices combined with silicon [282]. Film growth by sputtering was investigated by NEC using a two-layer epitaxial buffer on silicon, MgAl₂O₄/BaTiO₃ [283]. The two layer buffer was needed to provide for a lattice match and a chemically compatible substrate for film growth. Later, these buffer layer substrates supplied to Bellcore in a collaborative experiment [269] resulted in the achievement of the first respectable current densities at 77K on a silicon substrate, $J_c = 8 \times 10^5 \text{ A/cm}^2$.

An area of research that touches on both substrates and patterning, and also transcends the boundary of film materials and device work is the single grain boundary studies performed at IBM on epitaxial films grown on SrTiO₃ bicrystal substrates [284,285,286]. So far this type of interdisciplinary study has remained unique to this laboratory.

6.3.3 High- T_c Devices

In contrast to the roughly comparable status of film growth activity in the U.S. and Japan, the U.S. has tended to outpace the Japanese in accomplishments

related to demonstrating potentially useful high- T_c devices or device-related properties. This is reflected in the greater number of entries for U.S. work in the bottom half of Table 6.4, which is starting to reflect steps towards demonstrating useful prototype superconducting devices in the areas of SQUID magnetic sensors and of microwave electronics. This present favorable position of U.S. high- T_c device-related research seems to be a reflection of the greater U.S. emphasis and experience with analog superconducting devices and also, perhaps, of the broader educational background of the U.S. research community. While it is a big advantage to have analog superconducting electronics expertise in order to contribute to the presently active areas of high- T_c device research, this is not true for digital superconducting electronics expertise. Low- T_c digital Josephson research activity is at a much greater circuit and integrated process complexity level than is possible to practice at present in high- T_c research. For Japanese low- T_c device research groups focused on digital integrated circuits, it is thus an enormous transition to be able to contribute to the materials and device advances needed at the present stage of development of high- T_c superconductivity. As a result, the digital Josephson groups in Japan have by-and-large not been the source of the major high- T_c accomplishments in Japan.

As described earlier in this chapter, there is research on low- T_c SQUID sensors in both the U.S. and Japan, but the U.S. has played more of a leading role in this research. In the early days of high- T_c superconductivity, there were respectable early demonstrations of d.c.- and/or r.f.-SQUID functionality from a number of laboratories in both the U.S. and Japan as well as in other countries. Among these early achievements, the highest operating temperature of a SQUID appears to remain at the 98.6 K value reported for a Sanyo Tl-BaCaCuO device in June 1988 [287]. For the most part, however, the more meaningful systematic work has come from U.S. laboratories. Researchers at U.C. Berkeley and Stanford have collaborated on flux noise studies of high- T_c films that might be used in devices and have shown that higher quality films (as judged by epitaxy and current density) have lower flux noise [288,289]. IBM researchers in Yorktown and Almaden have demonstrated [265,266,267] a basic single-level SQUID employing naturally-occurring grain boundaries in TlBaCaCuO films with an energy sensitivity of 10^{-29} J/Hz at 10 Hz and almost ideally low noise (for the given device size at 77 K) above about 1 kHz, a noise level that appears adequate for many applications [290]. Recently workers at Yokogawa Electric [291] have reported on a TlBaCaCuO SQUID, similar to the one at IBM, with noise approaching that of the earlier IBM report. The road to useful commercial SQUIDs will be a long one, with meticulous thin film process developments being key for further developments. For instance, still lacking are demonstrations of multi-level coupling structures and of the

fabrication of reproducible Josephson elements (of some type).

In the case of high frequency properties of superconducting film devices, there has been little Japanese activity, although there is considerable U.S. and some European activity. In this area, the first demonstration of losses in a high temperature superconductor that are far less than those attainable with cooled normal metals came from measurements at Wuppertal of films grown by pulsed laser deposition at Siemens [268]. A number of U.S. laboratories have constructed resonators with one or more superconducting layers. With regard to devices made with films, researchers from Stanford University, working with Hewlett Packard, studied the temperature dependence of the penetration depth in what appears to be the first experiment with an all-high- T_c microstrip (two-levels of superconductor) resonator [271]. In a collaboration between SRI's David Sarnoff Laboratory, Rutgers, and Bellcore, a filter with both superconducting and normal metal films was constructed with losses at 77 K lower than are attainable with normal conductors alone [292]. MIT Lincoln Laboratory and AT&T Bell Laboratories reported [293,294] the first loss data at 77 K in an all-high- T_c stripline (three levels of superconductor) resonator that were significantly below those possible with cooled normal metals. For very short pulse propagation there have also been a number of demonstration experiments in the U.S. Researchers at Cornell University and the University of Rochester first demonstrated that high- T_c transmission lines could maintain the fidelity of sharp risetime pulses [295], and workers at AT&T recently succeeded in demonstrating lower loss picosecond pulse propagation on a YBaCuO coplanar strip line at 77 K than was possible with a gold line [270].

We saw no evidence in Japan of the superconducting infrared detector research that is active in the U.S. So far there have been no substantial device demonstrations at 77 K resulting from this work, although research has indicated that bolometric applications at 77 K appear feasible [296]. Whether or not nonbolometric devices at 77 K will be possible remains a controversial subject.

6.4 Concluding Comments on Electronics

Overall, it might be said that the U.S. and Japan are at roughly equal strengths in their superconducting film and electronics research. The research emphasis in the two countries is substantially different, however. In low- T_c superconducting electronics Japan has for the last 6 years continued a strong digital circuits effort and this has resulted in substantially more advanced low- T_c processing there. Of special note are recent laboratory demonstrations of 4-bit digital Josephson microprocessor chips that are much more complex than any low- T_c circuits

being attempted in the U.S. The U.S., on the other hand, has had a much greater emphasis on analog superconducting circuits, and enjoys a substantial research lead in a variety of low- T_c superconducting analog circuits. In the high- T_c areas, the overall thin film growth activities in the two countries are roughly on a par with each other, but the U.S. efforts seem to couple these film activities more effectively to prototype device demonstration efforts. This may reflect a broader outlook and educational background on the part of U.S. researchers, or may be just a reflection of the fact that the early thin film high- T_c devices are analog devices with which U.S. research groups have substantially greater experience. In many cases, low- T_c device experience seems to carry over well into high- T_c device research.

In general, it is difficult to identify an over-riding application theme for high- T_c electronics research in Japan. It appeared that many Japanese laboratories were willing to make long-term commitments to thin-film research without sharply defined applications goals. The assessment of the potential of high- T_c electronics applications given by both university and industrial laboratories was rather pensive, stressing the likelihood of a long development cycle. Laboratories doing film work either articulated no specific application goal, or referred to rather general application goals in the passive device area - such as low loss, high frequency interconnections of high electron mobility transistors (HEMTs). Perhaps this is the most distinguishing feature of the Japanese efforts relative to U.S. efforts in thin film electronics - strong commitment to materials synthesis projects even in the absence of short-term device or applications goals.

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Appendix A

Personnel and Agenda

A.1 Biographical Sketches of JTEC Panel Members

A.1.1 Mildred S. Dresselhaus

Mildred S. Dresselhaus is an Institute Professor of Electrical Engineering and Physics at the Massachusetts Institute of Technology, and a former Director of the Center for Materials and Engineering at MIT. She received her Ph. D. degree from the University of Chicago in 1958, and joined the MIT faculty in 1967. She has been active in the study of a wide range of problems in the physics of solids, including semimetals, graphite and other layered materials, intercalation physics, and recently has returned to the study of superconductivity, the subject of her Ph. D. Thesis. She has served as President of the American Physical Society (1984), and is a member of the National Academy of Engineering and the National Academy of Sciences, and has served as a Council Member of both Academies.

A.1.2 Robert C. Dynes

Robert C. Dynes is currently Director of the Chemical Physics Research Laboratory at AT&T Bell Laboratories. This laboratory has the responsibility for research in the area of the physics of new materials and novel configurations of materials with potential technological relevance. Studies in this laboratory range from new electronic materials to photon, electron and ion beam interactions with solids and liquids. His personal research interests include studies of electron properties and transport in semiconductors and metals including superconductors. His work has embraced such phenomena as the metal insulator transition, electron localization, strong coupled superconductors and the

low temperature thermodynamics of solids and liquids. Dynes came to Bell Laboratories in 1968 following a Ph.D. in physics at McMaster University. In 1974 he was appointed Head, Semiconductor and Chemical Physics Research Department. In 1981, he became Head, Solid State and Physics of Materials Research Department and in 1983 he assumed his present position. He is a Fellow of the American Physical Society, a Fellow of the Canadian Institute for Advanced Research (CIAR) and sits on divisional review committees for Oak Ridge National Laboratory, Los Alamos National Laboratory, and the National Research Council of Canada and sits on the Advisory Board for the Alfred P. Sloan Foundation. Dynes holds five patents in the area of superconductivity and transport of new materials, and has published many articles in the area of low temperature physics, superconductivity and transport. He was recently elected to the National Academy of Sciences.

A.1.3 William J. Gallagher

William J. Gallagher is a Research Staff member at the IBM Thomas J. Watson Research Center. After receiving his B.S. in Physics summa cum laude from Creighton University in 1974, and his Ph.D. in Physics from MIT in 1978, he joined IBM. For his first five years at IBM he worked on the scientific and engineering aspects of Josephson computer technology. After the termination of that program later in 1983, he became manager of the Exploratory Cryogenics research group, the position he now holds. Dr. Gallagher's research activities are primarily in the physics and applications of superconducting electronic devices. Dr. Gallagher is a member of the American Physical Society and the IEEE. He has served as Assistant to the Chairman of the APS Forum on Physics and Society, and is currently on the Board of Directors of the Applied Superconductivity Corporation. He has additionally served on study panels convened by the National Research Council, the National Science Foundation, the Office of Naval Research and the Office of Technology Assessment. He is on the editorial board of the Journal of Superconductivity and on the Assessment Panel of the Center for Electronics and Electrical Engineering of the National Institute of Standards and Technology.

A.1.4 Paul M. Horn

Paul M. Horn is Director of Physical Sciences in the IBM Research Division, Thomas J. Watson Research Center in Yorktown Heights, NY. He graduated from Clarkson College of Technology and received his Ph.D. degree from the University of Rochester in 1973. From 1973 to 1979 he was Assistant and Associate Professor of Physics at the University of Chicago. He joined IBM

in 1979 as a research scientist and was appointed Acting Director of Physical Sciences in 1987 and Director in 1988. Horn has worked on a wide variety of problems in solid state physics, including, surface physics, critical phenomena, phase transitions, the structure of quasicrystals and high temperature superconductivity, and has over 85 technical publications. He is a member of the American Physical Society Planning Committee, the National Steering Committee for Advanced Neutron Sources, and the Executive Committee of the Argonne Advanced Photon Source Users Organization, among others, and is also a former Associate Editor of Physical Review Letters. Horn was an NSF Graduate Fellow, was an Alfred P. Sloan Research Fellow in 1974-78, is a Fellow of the American Physical Society (APS), and in 1988 was elected to the APS Panel on Public Affairs. In 1988 he was recipient of the Bertram Eugene Warren Award given by the American Crystallographic Association for his studies of two-dimensional phases and phase transitions in adsorbed layers.

A.1.5 John K. Hulm

Dr. John K. Hulm obtained his B.S., M.S. and Ph.D. in Physics at Cambridge University, England, 1941-1949. He served as a radar officer at the Royal Aircraft Establishment, Farnborough, 1943-1946. He was appointed Union Carbide Fellow at the University of Chicago in 1949 and Assistant Professor in 1951. He joined the Westinghouse Research Laboratories in 1954 and served the company in research and management positions until partial retirement in 1988. Dr. Hulm's last full-time management appointment was Director of Corporate Research. He was appointed Chief Scientist Emeritus in 1988. Dr. Hulm has 36 years of experience in teaching physics and research in fundamental properties of materials primarily through investigations at very low temperature, including thermal conductivity, dielectric properties, electrical conductivity, superconductivity, ferromagnetism, adsorption, and diffusion. Under Dr. Hulm's direction, Westinghouse succeeded in 1961 in developing the first extremely high-field superconducting magnet. Internationally known for his cryogenic research, Dr. Hulm was honored by the Franklin Institute in 1964 with its John Price Wetherill medal in recognition of his discoveries in low-temperature physics. He received the American Physical Society International Prize for new materials in 1979. In 1980, he received the Westinghouse Order of Merit for his pioneering efforts in the application of superconductivity to electric power technology. Dr. Hulm was elected member of the National Academy of Engineering in 1980 and member of the National Academy of Sciences in 1988. He has served on a large number of Government Committees and Study Groups. Current appointments include: National Materials Advisory Board (NRC), Solid State Sciences Committee (NRC), Board of Overseers,

Superconductivity Super-collider (URA), Advisory Board, Division of International Affairs (NSF), Advisory Committee, Francis Bitter National Magnet Lab (MIT), Advisory Board, Science & Technology Center (NSF).

A.1.6 M. Brian Maple

M. Brian Maple has been professor of Physics at the University of California, San Diego, since 1981. He received his Ph.D. in Physics from UCSD in 1969. His current research interests include superconductivity, magnetism, valence fluctuation and heavy fermion phenomena, low temperature and high pressure physics, surface science and catalysis. Dr. Maple received a John Simon Guggenheim Memorial Foundation Fellowship in 1984, and was named a 1987 University of California, San Diego, Distinguished Alumnus of the Year, and the 1988 San Diego State University, College of Sciences, Distinguished Alumnus of the Year. He is a Fellow of the American Physical Society and served as the Chairman of the APS Division of Condensed Matter Physics in 1987. Dr. Maple has been the Chairman or Co-Chairman of six International Conferences, has co-edited two Conference Proceedings and two volumes on Superconductivity in Ternary Compounds, and has served as Guest Editor of a special 1989 volume of the Materials Research Society Bulletin on "High Temperature Superconductivity". He currently serves on Advisory Committees for Argonne, Lawrence Livermore, Los Alamos and Oak Ridge National Laboratories. In 1986, he was a member of the U.S. Delegation to the Annual Meeting of the Japanese Special Program on Superconducting Materials in Tokyo.

A.1.7 Rod K. Quinn

Rod K. Quinn is Director of the Exploratory Research and Development Center and of the new high-temperature superconductivity research center at Los Alamos National Laboratory. These Centers will promote interactions with industry, other laboratories and universities as well as coordinate and focus Laboratory research in high-temperature superconductivity. Quinn joined Los Alamos in 1986 as an associate division leader and program manager in the Chemical and Laser Sciences Division following a 19-year career at Sandia National Laboratories in Albuquerque, N.M. He earned a doctorate in physical chemistry from the University of Texas at Austin in 1967, when he became a staff member at Sandia, and later directed research programs in electrochemistry, solid-state chemistry and inorganic materials synthesis and characterization. He was project leader for Sandia's successful long-life thermal battery development program, supervisor of the Exploratory Batteries Division at Sandia from 1978-82 and supervisor of the Inorganic Materials Chemistry Division

from 1982-86. He is a member of the American Chemical Society, a fellow of the American Institute of Chemists and active in the Materials Research Society, in which he has held several national offices.

A.1.8 Richard W. Ralston

Richard W. Ralston is the leader of the Analog Device Technology Group at the MIT Lincoln Laboratory. Since 1988, Dr. Ralston has been Director of a Consortium in Superconductive Electronics which involves participants from several MIT departments, the Francis Bitter National Magnet Laboratory, and two directorates of the Air Force Rome Development Center. An expansion of the consortium activity to include the IBM Research Division, AT&T Bell Laboratories and other industrial, university and government laboratories is now underway. He received the Ph.D. degree in applied physics from Yale University in 1971, working on two-dimensional quantum effects of electrons in inversion layers at cryogenically cooled silicon surfaces. From 1965 to 1966 he was a staff member at Bell Laboratories, Murray Hill, NJ, where he participated in the development of microwave devices. In 1971 he joined the MIT Lincoln Laboratory staff, initially working on tunable diode lasers and heterostructure waveguides in a 3- to 16-micrometer wavelength region. Since 1974, he has been working in the Analog Device Technology Group, which he currently leads. His technical activities presently include the development of charge-coupled devices and microwave superconductive integrated circuits for wideband, and real-time signal processing, and include efforts in low- and high-temperature superconductive technology development. Dr. Ralston has served as an invited short-term visiting researcher in 1987 on the topic of Josephson device technology at the Electrotechnical Laboratory in Tsukuba, Japan, and has participated in several joint Japan-U.S. Josephson Device Workshops. He holds several patents and has authored many technical papers.

A.2 Itinerary of JTEC Panel in Japan

Date	Laboratory	JTEC Members visited
May 30	Mag-lev Test Site	Hulm
May 31	Furukawa Electric	Hulm
May 31	MITI	Hulm
June 1	Fujitsu	Dynes, Ralston
June 1	NEC	Dresselhaus, Gallagher
June 1	RTRI	Hulm
June 2	KEK	Dresselhaus, Hulm
June 2	NTT (Ibaraki)	Dynes, Gallagher, Ralston
June 2	Hitachi (Ibaraki)	Dresselhaus, Hulm
June 3	Tohoku University	Dresselhaus, Dynes, Gallagher, Hulm, Ralston
June 5	ISSP (U. of Tokyo)	Dresselhaus, Dynes, Gallagher, Hulm, Maple, Quinn, Ralston
June 5	ERATO briefing	Dresselhaus, Dynes, Gallagher, Hulm, Maple, Quinn, Ralston
June 5	U. of Tokyo	Dresselhaus, Dynes, Gallagher, Hulm, Maple, Quinn, Ralston
June 6	Electrotechnical Lab.	Dresselhaus, Gallagher, Hulm
June 6	NIRIM	Maple, Quinn
June 6	Hitachi (Kokubunji)	Ralston
June 6	NTT (Musashino)	Dynes
June 6	NRIM	Dresselhaus, Hulm, Maple, Quinn
June 7	ISTEC (Nagoya)	Dresselhaus, Dynes, Horn, Hulm, Maple, Quinn, Ralston
June 7	Sumitomo	Dresselhaus, Dynes, Horn, Hulm, Maple, Quinn, Ralston
June 8	Matsushita	Dresselhaus, Horn, Hulm, Maple, Quinn
June 8	Mitsubishi	Dresselhaus, Horn, Hulm, Maple, Quinn
June 8	Organic Superconductor briefing	Dresselhaus, Horn, Maple
June 9	ISTEC (Tokyo)	Dresselhaus, Horn, Hulm, Maple, Quinn
June 9	Toshiba	Dresselhaus, Horn, Hulm, Maple, Quinn

A.3 Biographical Sketches of JTEC Review Panel Members

A.3.1 Richard D. Blaugher

Richard D. Blaugher is Manager of High Temperature Superconducting Materials and Electronics at Intermagnetics General Corporation (IGC) in Guilderland, New York. He has been directly associated with superconductivity research for over 30 years. His research has been directed at materials, large-scale applications in generators and magnets, and more recently he has been working on Josephson-based superconducting electronics. He currently directs the advanced superconducting materials research at IGC. Prior to joining IGC, he was manager of the Superconductivity and Electronics Department at the Westinghouse R&D Center. He has served on numerous government committees on superconductivity and also has served on the Applied Superconductivity and Cryogenic Engineering Boards. He has published over 70 papers related to superconducting materials and applications.

A.3.2 Bobby D. Dunlap

Bobby D. Dunlap is Director of the Materials Science Division of the Argonne National Laboratory. He has been associated with Argonne since receiving his Ph.D. in Physics from the University of Washington in 1966. His principal research interests have involved studies of the magnetic and electronic properties of rare-earth and actinide materials, with emphasis in the last several years on materials which display both magnetic ordering and superconductivity, and on high transition temperature oxide superconductors. He has authored or coauthored 180 journal articles. Dr. Dunlap is a Fellow of the American Physical Society and an Editor for *Physica C: Superconductivity*.

A.3.3 David S. Ginley

David S. Ginley, presently Supervisor of the Semiconductor Materials Division at Sandia National Laboratories, was born in Denver, Colorado in May 1950. He received his B.S. in Mineral Engineering Chemistry from the Colorado School of Mines in 1972 and his Ph.D. in Inorganic Chemistry from MIT in 1976. Since that time he has been at Sandia National Laboratories. His primary interests are in the applications of inorganic chemistry to the synthesis and processing of materials. Some of his areas of interest have been photochemistry, photoelectrochemistry, improved efficiency in polysilicon solar cells,

and novel chemical sensors. Currently his primary interests are in high temperature superconductors and the novel processing of compound semiconductors. He currently supervises a research group developing new materials and device structures with MOCVD and MBE in the compound semiconductors and high temperature superconductors. Dr. Ginley has written or co-authored over 150 technical papers and holds 5 patents. He is currently an editor for the Journal of the Electrochemical Society and the Chairman of the Energy Technology Division of the Society.

A.3.4 Richard L. Greene

Richard L. Greene is Director of the Center for Superconductivity Research and Professor of Physics at the University of Maryland. He received his Ph.D. degree from Stanford University in 1967 and remained there as a research associate until 1970. He then joined the IBM Research Division and held a variety of research and management positions at both the San Jose (Almaden) and Yorktown Heights laboratories until accepting his present position in Maryland in 1989. His personal research has involved many problems in condensed matter physics, including properties of low dimensional metals, organic superconductivity, and high-temperature superconductivity. He has authored over 115 technical publications and is a Fellow of the American Physical Society. Dr. Greene has been on the organizing and program committees of many international conferences and currently serves on the advisory committee for the Francis Bitter National Magnet Laboratory.

A.3.5 Richard E. Harris

Richard E. Harris is Group Leader of the Cryoelectronic Metrology Group at the National Institute of Standards and Technology (NIST) Boulder Laboratories. He received his B. S. in Physics with High Distinction from the University of Rochester in 1963, followed by a M. S. in 1965 and a Ph. D. in 1969 from the University of Illinois. He joined NIST in 1975 after working at the United Technologies Research Center for 6 years. In 1980 he spent one year at the IBM Zurich Research Laboratories. Dr. Harris' research has dealt with flux motion in superconductors and both fundamental and device aspects of superconductors. In 1979 he was instrumental in beginning the Workshop on Superconducting Electronic Devices, Circuits and Systems and continues an active role in this workshop, serving as chair in 1985. He serves on the Board of Directors of the Applied Superconductivity Conference and is a member of the American Physical Society, the IEEE, and the AAAS. He has also assisted the Agency for International Development and has served on study panels for

the Office of Technology Assessment and the Office for the Under Secretary of Defense for Acquisition.

A.3.6 Miles V. Klein

Miles V. Klein is Professor and Director of the Science Technology Center for Superconductivity (STCS) at the University of Illinois at Urbana-Champaign. He received his Ph.D. degree from Cornell University at the beginning of 1961 and spent 1961 as an NSF Postdoctoral Fellow at the Max Planck Institute for Metal Research in Stuttgart. He became a faculty member at the University of Illinois in 1962. He uses optical techniques, primarily Raman scattering and photoluminescence to study semiconductors and metals, especially superconductors. His group was the first to observe the gap, 2Δ , using Raman scattering. He is a Fellow of the American Physical Society and a Senior Member of the IEEE. He became Director of STCS upon its funding by NSF in February, 1989. Klein has twice served on the Executive Committee of the Condensed Matter Division of the American Physical Society, the second time as Chairman, and has served on, and chaired, the Oliver Buckley Condensed Matter Prize Committee of the American Physical Society.

A.4 Agenda of kick-off meeting, March 31, 1989

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- 9:30 Coffee and Doughnuts
- 10:00 Introductions - George Gamota¹
- 10:10 Overview of JTEC - Duane Shelton
- 10:25 Overview of NSF's Superconductivity Activities and Interests - Frank Huband
- 10:35 Overview of Other Agencies' Interests
- 11:00 Panel Chairwoman's Remarks - Mildred Dresselhaus
- 11:15 Panel Discussion on Study Scope and Allocation of Tasks²
- 12:30 Working Lunch (Served in Room)
a) Administration of Study - Stephen Gould
b) Report and Workshop - George Gamota
c) Literature Support and Japan Trip - Alan Engel
- 1:15 Additional Panel Discussion³
- 3:00 Solicitation of Panel Support Requirements
- 4:00 Meeting Adjourns
- Notes:
1. Dr. Gamota will chair the meeting until 11:30; Prof. Dresselhaus thereafter.
 2. Prof. Dresselhaus suggests a possible partition:
(1) Science, (2) Materials, and (3) Applications.
 3. To focus the study, Prof. Dresselhaus suggests that the panelists each prepare a brief summary of U.S. research in their area before the trip to Japan.
 4. Please prepare a list of Japanese labs that should be visited in your area of expertise, preferably with the name of a contact.

A.5 Agenda for Oral Report Meeting, August 1, 1989

Superconductivity Workshop

August 1, 1989

1800 G Street, NW, Washington, DC, Room 540

DRAFT AGENDA

- | | | |
|-------|---|---------------------------------|
| 9:30 | Registration (coffee and continental breakfast) | |
| 10:00 | o Welcome to NSF | |
| 10:10 | o Review of JTEC | Huband |
| 10:30 | o Introduction to Study | Dresselhaus |
| 10:50 | o Introduction to the Technologies | Quinn |
| 11:20 | o Science | Horn |
| 12:00 | o Lunch (served in meeting room) | |
| 1:00 | o Materials | Dynes |
| 1:40 | o Processing | Maple |
| 2:20 | o Electronic Applications | Ralston |
| 3:00 | o Electrical and Magnetic Applications | Hulm |
| 3:40 | o Review Comments | Discussants and
Participants |
| 4:00 | o Concluding Remarks | Dresselhaus |
| 4:20 | o Adjournment | |

Appendix B

Laboratory Visits

B.1 Government Laboratories

B.1.1 Electrotechnical Laboratory (ETL)

M.S. Dresselhaus

We (John Hulm, Bill Gallagher, Paul Herer and Mildred Dresselhaus) started off from our hotel in Tokyo at 7:15 am after a 6 am meeting with several members of the JTEC team. The trip to the Electrotechnical laboratory was done by taxi to Tokyo station, and a bus to Tsukuba, and a walk 10 minutes from the bus stop to the laboratory. We arrived early to the meeting room and had time for small conversation and watched the leaders of the Electrotechnical Laboratory (ETL) assemble. The visit was very well organized and we were shown as much as was possible in the available time.

As our meeting started, we were greeted by Dr. Masuru Sugiura, the Director-General and his Deputy Director-General, Dr. Hiroshi Kashiwagi. Dr. Sugiura, himself, gave us an overview of the Electrotechnical Laboratory. The ETL is the largest national institute in Japan, and is under the Agency of Industrial Science and Technology (AIST) of the Ministry of International Trade and Industry (MITI). The laboratory is also one of the oldest, being established in 1891 as a testing laboratory under the Bureau of Electrocommunications of the Ministry of Communications. This laboratory considers itself the best national laboratory in Japan and has spawned major laboratories, the most celebrated being the NTT Electrical Communications Laboratory in 1948. The ETL has been under AIST sponsorship since 1952. Its present structure dates back to 1970 and its present location in Tsukuba to 1979. In 2 years the laboratory will be celebrating its 100th anniversary, and they are proudly thinking about that occasion.

The laboratory employs 700 people with an annual budget of \$70 M. They are organized into four units: Electronics, Information Technology, Energy Technology, and Standards and Measurement Technology. There is no corresponding laboratory in the United States, the closest perhaps being the National Institute for Science and Technology (NIST, formerly the National Bureau of Standards).

In this laboratory about 60-70% of the research personnel are Ph.D.s, which is high for Japanese R&D organizations in industry and other national materials laboratories. About 10% of the current effort is devoted to superconductivity, or about 60 people (about 30 in conventional superconductivity, 10 in organic superconductivity and 20 in high- T_c oxide superconductivity). Of this group, 5% are foreigners, and Dr. Sugiura identified 3 foreigners currently working at ETL on superconductivity, one from the U.S. working on standards, one from England working on the mechanism for superconductivity, and one from Italy working on Josephson junction technology. About half of the present members of the superconductivity groups had been working with superconductors prior to the discovery of high- T_c superconductivity. With regard to the MITI budget for superconductivity, 10-15% of the total MITI budget goes to ETL. The budget figures for MITI support do not contain the costs for industrial participation; thus they estimate that 20-30% of the budget goes into personnel costs, and the rest into project support, equipment, etc.

With regard to the high- T_c program at ETL, there is presently not much interaction with industry and universities (on the order of 20-30 researchers), and these interactions are mostly developed by personal contacts. Most students working at ETL are undergraduates (and they are few). Overall there are less than 10 graduate students using the resources at ETL for their Ph.D. degrees. These figures were quite surprising compared to National Laboratories in the U.S.

Following the overview talk by Dr. Sugiura, and the question-answer period that followed, we had a briefing by Dr. Kajimura, who reviewed the MITI project on superconductivity. One of the superconductivity programs was a special research project on digital Josephson technology, and included R&D on all Nb and NbN integrated circuit technology. This low- T_c work has already had a major impact on the development of superconducting electronics capabilities at Fujitsu, Hitachi, and NEC. Another project using conventional superconductors involved R&D for a large magnet (outer radius of 70 cm) for a fast ramp-up of the magnetic field for nuclear fusion applications. ETL has a significant commitment to R&D on organic superconductors through their program on basic technologies for future industries. Under the "moonlight" project which involves R&D directed toward energy conservation technology, a new project was started in FY 1988 involving superconducting technology

for electric power systems, including superconductor rotor machines and the development of superconducting materials to support this industry. Superconductivity research has been designated as an area for international collaboration, bringing foreign scientists to work at ETL for extended periods. Many Divisions were participating in superconductivity R&D. All 3 sections of the Physical Science Division are involved with basic research on superconductors. The Materials Science Division seemed to focus their R&D on superconducting materials with potential for higher T_c , and in this division they were preparing and characterizing thin film oxide materials. In the Electron Devices Division, R&D on superconducting electronics was taking place while superconductors, SQUIDS and Josephson effects were being studied for metrology applications. Within the Superconducting Technology Section of the Frontier Technology Division was a large program on developing superconducting wires for magnets and finding applications for superconducting materials. The Superconductor Applications Section of the Energy Technology Division was working on superconducting machinery, refrigeration for this machinery, magnet design, superconducting generators and R&D for a high field pulsed magnet.

Dr. Jun Kondo, the discoverer of the Kondo effect and the only researcher with the honorary title of ETL Fellow, heads the Theory Group. He briefly spoke to us on their superconductivity theory program. They have 5 theorists in all (each having a Ph.D. degree), and they are mostly interested in the oxide superconductors, though they have some effort on calculating the energy levels for the organic superconductors. Their high- T_c theory efforts were directed toward calculation of the electronic structure, carrier distribution, Madelung energy, exchange interaction and spin orbit interaction effects, as well as study of the basic mechanisms of the high- T_c superconductors. Their organic superconductivity group included at least 6 researchers; and covered synthesis, property measurements and theory, with a lot of work on the BEDT-TTF system, which has shown T_c values above 10K. Over 20 members of ETL were involved in materials synthesis and characterization of the high- T_c oxide materials, and many of the same people were also involved in measurements of the physical properties. In the materials and property measurements projects there was some interaction with industrial visitors. One memorable work was the early identification of the space group of the Tl "1234" phase ($T_c=122.1K$) using beautiful TEM lattice imaging patterns to show the 4 copper layers separated by a calcium layers. Strong programs were in operation to study the electronic properties by EXAFS methods and magnetic properties using a variety of techniques. Oriented thin films of Bi-Sr-Ca-Cu-O were being grown by co-evaporation in a MBE machine. Superconductor-normal-superconductor (SNS) Josephson junctions had been fabricated from YBaCuO films at an early stage. On the laboratory tour we visited the Applied Physics Section and spoke

to people doing EXAFS measurements. We also saw their high- T_c film deposition laboratory which was impressive by the density of very fancy MBE and deposition equipment and by the large number of CuO_2 layers they could prepare in a controlled way.

DC SQUID studies based on NbN were still under active investigation for use as a magnetometer or gradiometer, in collaboration with researchers from industry and academia. With this technology they have developed a voltmeter with an accuracy of 10^{-8} , and this instrument has been used for the absolute measurement of the magnetic flux quantum with a noise figure 20 times better than commercial SQUID magnetometers and a sensitivity of $\sim 10^{-8}$. The Josephson technology was also being applied to a variety of circuit applications, such as a 10-bit ROM unit for a prototype computer, a 2-bit arithmetic logic unit using a four-junction logic gate, a high speed 1-kbit variable threshold Josephson RAM chip, an address control unit integrated circuit for a 4-bit microcomputer prototype. One interesting aspect of the Josephson technology program was the strong interaction with visiting scientists, thereby transferring the technology of building superconducting integrated circuits based on refractory Josephson tunnel junctions of sputtered Nb and NbN films. Some of this Josephson Technology has been used to observe fluxon reflections and fluxon-fluxon collisions in a transmission line. On the tour, Dr. Itaru Kurosawa showed us the Superconducting Electronics Laboratory with a heavy technical concentration of new multichamber deposition equipment being used to grow and study high- T_c film materials.

On the large scale applications, one of the highlights was the development of new fabrication processes for adding Ti to Nb_3Sn wires to improve their ductility more efficiently and with lower cost because of their easier manufacturability. Work is in progress to develop a high field fast pulse magnet. For this goal a forced cooled Nb_3Sn superconducting magnet composed of 9 double pancake coils has been fabricated and successfully tested at the high field test facility of ETL. On the tour we saw some of this very large equipment.

B.1.2 ERATO Program, including Quantum Magneto-Flux Logic Project

M.S. Dresselhaus

On June 5, we were invited to lunch in Tokyo with Mr. Genya Chiba, Director of the ERATO program, so that he could tell us more about the program. In the 1970's, there developed a consensus among the government Ministries that Japan needed more focused research programs than are normally provided by individual grants. By that time enough government research money

was becoming available, and some of this was channeled through the Science and Technology Agency (which is a Ministry) to the Research and Development Corporation of Japan (JRDC), a statutory corporation of the Japanese government, to start the ERATO program in 1981.

Some of the basic concepts behind the ERATO program are the following. Scientists (and technologists) are considered as creative artists (young sci-tech "performers"). The research themes and project Directors are selected by the Research and Development Council of JRDC, comprising both scientists and industrialists from the public and private sectors, and are recommended to the president of JRDC. It is the job of a group of about 10 people and the Director of the ERATO program (Mr. Chiba) to identify people and themes for the Council to consider. They put a great deal of effort into identifying especially creative, young individuals to become directors of the ERATO projects.

Each project leader will identify and recruit about 10-15 young scientists and engineers who can make significant contributions in the field of the research theme, about half from universities, and half from industry. Each project lasts for 5 years and is then terminated. To emphasize the finite lifetime of projects, the laboratories for each ERATO project are housed in rented space. The funding for each ERATO project is at the \$3 M/year level, with the idea that funding a talented person at a generous level will produce significant results within a 5 year period. One of the successes reported by Mr. Chiba was the synthesis of a polymer-based graphite film, something I knew about in the past, but did not know that it came out of an ERATO project.

With regard to the participants in the ERATO projects, the companies and universities involved have a positive attitude. About 90% of the participants have returned to their home institutions with valuable additional experience, something like an advanced post-doctoral program, and most of the returning people are soon placed in positions where they can create innovative research teams like those found in ERATO projects. For most of the participants, their ERATO experience is in an area not too far away from what they were doing before. With regard to inventions made through the ERATO projects, 50% of the rights belongs to the individual and/or their base company/institution and 50% to JRDC.

Thus far 7 projects have been completed, 11 are in progress, and 3 will begin in the fall of 1989. Almost all of the ERATO projects have been in the fringe area of basic science and emerging technology, because the R&D Council of the JRDC believe that it is these fields which attract the most creative people. Some of the areas that have been selected include quantum well devices; femtosecond chemical reactions; electron interference effects; picking up individual atoms from a surface; locating genes within the human genome.

Since our JTEC panel was involved with a superconductivity study, we

were particularly interested in ERATO projects in superconductivity. Thus far, they have chosen only one superconductivity-related project: Professor Eiichi Goto of the University of Tokyo is now studying flux quanta, and the idea of using single flux quanta as a bit of information. In this project Professor Goto will explore circuits and applications of the Quantum Flux Parametron (QFP), which he invented about 30 years ago in the context of a ferrite core. The parametron is here used in the context of a Josephson junction element in a magnetic flux loop. This technology benefits from very high speeds and extremely small power consumption, and is being examined for a variety of digital applications including next generation computers.

The Technical Manager is Dr. Yasuo Wada, on assignment from the Hitachi Central Research Laboratory, who spent about a year at MIT a decade ago where he interacted strongly with the Dresselhaus group. Under the direction of Dr. Goto, Wada manages a team of 17 researchers from 3 different private companies, three universities and four foreign countries, in addition to 7 support staff coming to a total of 23 team members. The project consists of three groups which conduct research in the facilities of their home institutions, and each of the four collaborating organizations makes a unique contribution: Hitachi contributes an excellent fabrication facility for Josephson technology, ULVAC contributes magnetic shielding and vacuum technology and Mitsui Systems Research contributes systems and software expertise, all of which Professor Goto feels to be necessary for the success of the project. In this consortium, researchers at three different locations are supported by ERATO funds and report to Professor Goto. The benefits to each of the companies is the development (through government support) of advanced technology which may perhaps be commercialized at some future time, as well as access to some exceptionally talented, young university researchers, who may eventually join their companies.

The ERATO program has intentionally not been involved with high- T_c superconductivity because the Japanese leaders feel that this subject is being well supported by other sources. The ERATO program has been evaluated after its first 5 years of operation and is considered to be a success in terms of training young people, enriching their careers and enhancing the Japanese infrastructure for R&D. The program has thus far supported 1500 publications. Alan Engel, who worked for us in arranging the laboratory visits for the JTEC study, is himself a former ERATO researcher and at present is the overseas liaison representative for the ERATO program. In the first six months of 1989, the ERATO program has had 260 overseas applicants, 10 of which have been selected from this applicant pool. Currently there are 12% foreign researchers in the ERATO program and it is hoped to increase that percentage to 30%. The goals of the ERATO program are to create a favorable environment within

which innovative research could flourish.

Since the ERATO program crosses the traditional boundaries of the various Ministries working in science and technology, this program has stimulated a competitive spirit among these institutions, resulting in the creation of similar programs. We learned for example that the Ministry of Education is not enthusiastic about the ERATO program and its projects, especially when the projects involve people at universities who have traditionally been funded by them.

B.1.3 International Superconductivity Technology Center (ISTEC)

M.S. Dresselhaus

ISTEC (International Superconductivity Technology Center) is a new experiment in Japan for coupling industry to basic and applied research. The concept is largely due to Professor Shoji Tanaka, who was the first to develop a national thrust program in new superconducting oxide materials in 1984 and in whose laboratory the pioneering discovery by Bednorz and Müller of high- T_c superconductivity was first confirmed. The ISTEC laboratory was established in January 1988 and the building was occupied in November 1988. At the time of our visit 7 months later, 70% of the equipment and most of the people were in place. Serious scientific work in the laboratory started two months before our visit.

The funding for the laboratory has three components: one is the initial contribution by each full member company (\$800 K), the second is the on-going annual \$100 K fee for membership, and the third category is direct support of about \$6.8 M of the total research budget (\$17 M/year) from MITI. Because of their success in getting companies to become supporting members (111 companies had joined by the time of our visit), ISTEC has a generous budget. Of these 111 companies, 65 of the companies are ordinary supporting members and 46 companies are full supporting members. Foreign companies can also join, and 7 have elected to do so, 5 of these being from the U.S., and 2 from Europe. Each full member company is allowed to send up to 2 researchers to work at ISTEC, while also paying their salaries. At present ISTEC has 86 researchers of whom 75 have come from supporting companies. The remaining 11 (including one foreign researcher from MIT) are directly supported by ISTEC.

The activities of ISTEC include research work, the sponsorship of one large symposium/year, the publication of a journal [14] (4 issues/year) in Japanese and English, the sponsorship of a workshop in high- T_c superconductivity for ~ 170 participants, and the sponsorship of surveys and studies on high- T_c

superconductivity.

Our visit to ISTEK occurred on one rainy Friday morning, June 9, 1989. Leaving the Akasaka Tokyu Hotel at about 9:15 am after a one hour progress and planning meeting of our JTEC group (Brian Maple, John Hulm, Rod Quinn, Paul Horn and Mildred Dresselhaus), we went to ISTEK by subway and then on foot in the rain from the nearest Metro station. Just as we arrived at ISTEK, so did Dr. Nobuyuki Kambe of NTT, who had taken his Ph.D. from MIT, and served in part as our facilitator.

To keep the laboratory clean, we were given plastic baggies at the laboratory entrance to put over our shoes. We were then ushered into one of their smaller conference rooms for a briefing. After the usual greetings and exchange of name cards, we were served some hot green tea, and the action started.

Since many of us knew Dr. Shoji Tanaka, the Director of the Superconducting Research Laboratory, he started the briefings, which were soon taken over by Dr. Naoki Koshizuka, Tanaka's deputy director and Director of Division I. In Dr. Koshizuka's briefing, he covered the organization of the overall ISTEK organization and the Superconducting Research Laboratory (SRL), including the ISTEK branch laboratory at Nagoya, which we had seen two days earlier.

We then heard briefings from the heads of each of the divisions. Dr. Naoki Koshizuka described the activities of Division I, Physics and Characterization, consisting of 13 research scientists, 1 visitor and 2 students. This division had two foci: (1) fundamental studies on the physical properties of the new superconductors and (2) the development of new characterization techniques. Under the first heading they were conducting studies on the structure (TEM, SEM, x-ray diffraction), electronic properties (specific heat, magnetoresistance, and magnetic resonance), dynamic properties of fluxoids (SQUID and a.c. susceptibility studies), optical and surface electronic properties (IR, Raman, XPS, UPS). In the second category they had high pressure studies using a diamond anvil apparatus, measurements of the critical current, and of the critical field H_c using pulse techniques and specific heat measurements. They were planning experiments to observe fluxoids using a magneto-optical technique and surface tunneling studies using a scanning tunneling microscope and scanning tunneling spectroscopy. Paul Horn asked them about their studies of the normal state properties and found that the normal state was not heavily studied. With regard to the magneto-optical studies, they told us of their plans to follow fluxoid motion dynamically by depositing EuS on high- T_c materials. They were planning to use the pulsed high field magnets at the ISSP for their high field fluxoid studies, and their own superconducting magnets for studies below 10 tesla.

A briefing on Division II Ceramic Materials was given by Dr. Hisao Yamauchi, who headed the division, consisting of 20 research scientists and 1

student. Their research was on the search for new superconducting ceramics (copper oxides, oxides not containing copper, and other ceramics), the development of present high- T_c superconducting oxides and the analysis, characterization and modeling of these high- T_c superconductors, including the temperature dependence of the resistivity and magnetic susceptibility, crystallographic studies, Hall effect and thermoelectric effect studies and modeling.

Professor Shoji Tanaka was himself leading Division III, the organic superconductor division, while looking for a permanent director for this division. This group now consists of 4 research scholars, and one student. Their program focused on the development of organic superconductors, the search for new organic superconductors, measurement of their physical and chemical properties, optical properties, the isotope effect, chemical analysis and theoretical modeling. Dr. Hatsumi Urayama-Mori, who is now at ISTECC Nagoya, was making the samples. The focus of the entire organic superconductor group is currently on basic science issues.

We then heard an overview presentation from Dr. Yuh Shiohara on Division IV on Chemical Processing. The division consists of 15 researchers, 2 students and 1 visitor from MIT (from the Cima/Bowen ceramics group). The research of this group was on developing thin films, thick films, wires and tapes using vapor phase epitaxy (VPE) and chemical vapor deposition (CVD), melt-solidification processing with which they were having good success in increasing critical current densities, and chemical solution processing (sol-gel coprecipitation and drying), with which they were having less success but felt that it was important to pursue because of the potential applications, and finally solid state powder ceramic processing. This group also makes single crystals for use by members of Division I and also thick tapes, wires and films.

Next we heard from Dr. Hisao Yamauchi, who was speaking in place of Dr. Tadataka Morishita, head of Division V on physical processing, who was attending a conference on high- T_c superconductivity elsewhere in Japan. This group presently consists of 18 researchers and 1 student. Division V was concerned with the development of fabrication processes for thin films with precise compositional control which are compatible with semiconductor processing, stressing the preparation of films at low processing temperatures and growing the films in-situ. The other main goal of this group was in the processing of the superconducting oxide films into useful forms, including fundamental studies of the physical properties of the interfaces with other superconductors, superconducting oxides, semiconductors and insulators, including multilayer capabilities. For their thin film work, they were interested in sputtering, MBE, and laser ablation, and were using ion assisted processing, and lithographic techniques for sputtering. They are expecting to have a focused ion beam apparatus soon for lithography and etching.

The last division at ISTECC Tokyo was a computer assistance division which is intended to provide assistance to researchers in all the divisions.

Following these presentations on the organization of ISTECC, three research presentations were planned, but because the time was short, only two presentations were actually given. The first presentation was by Dr. Masahito Murakami from Nippon Steel, who reported his results on the melt processing of "123" materials into thick films and reported on his efforts to achieve high- J_c in a magnetic field. His observation that the change in magnetization did not depend on the sample size implies that the J_c is limited by grain boundaries rather than sample size. He therefore did a lot of detailed work on the phase diagram to get the "211" phase into very small particles, finely distributed throughout the material. Then he did detailed studies on cooling in a magnetic field. Samples with the best microstructure had little crystalline orientation. There was then some discussion about the merits of transport vs. magnetization measurements for studying J_c . Since the magnetization measurement gets contributions from all directions, these measurements contain a lot of information about defects. Time dependent magnetization measurements were used to study flux creep, pinning forces and pinning energies. This was very nice work.

We next heard from Dr. Setsuko Tajima, a lady assistant professor from the University of Tokyo, who was now an ISTECC employee. She had been studying optical properties on all kinds of oxide superconductors looking at the effect of doping on the plasma frequency. She also was doing reflectivity measurements on the electron system $Nd_{2-x}Ce_xCuO_4$. She and G. Thomas of Bell AT&T were identifying infrared structure with the superconducting band gap. The presentation was too fast to get the full details of the work, but reprints were provided to help us along.

Following the two presentations, we had a tour of the laboratory. In the lab tour we heard that about 70% of capital equipment had already been delivered. Their building was rented because of the idea that ISTECC is to be in existence for 10 years and then would be disbanded. During our visit the researchers were heavily involved in setting up state of the art equipment: 2 x-ray systems, a 400 kV TEM, 2 SEMs, 2 SQUID magnetometers, and an optics laboratory was being set up, etc. Each Division was being set up in one laboratory. The laboratories looked quite crowded, but the equipment was new and top of the line. In one of the laboratories alone, we saw about \$10 M worth of equipment. We were shown two of the five laboratories. They were very impressive.

Professor Tanaka thinks that what it takes to make progress in this high- T_c field is equipment at the level of sophistication of the semiconductor industry. Thus they were using the \$0.8 M per company initiation fee for capital equipment and space renovation. We also saw the crowded office space of the

researchers, with many cubicals separated by sound barriers. The offices were very small, attractively laid out by the standards seen in other Japanese laboratories, but lacking the quiet and privacy that researchers in U.S. laboratories are accustomed to. We were also shown some very attractive conference and seminar rooms. All in all they have made a showpiece of this laboratory on an international scale. On the basis of all we saw, world-class research should emerge from this laboratory. There seems to be a problem in attracting top people for Division Heads because the job doesn't lead to much, since after 10 years the laboratory will be disbanded. Tanaka's stature has been needed to pull off this operation, to get money from companies, to sell the concept of high- T_c , superconductivity and the optimism that there would be products in the long term, to create the idea of a national collaborative program with many industries seriously committed to superconductivity. One of the barriers to ISTEAC is the belief of each participant company that it can do its own thing independently if it chooses to. Japanese companies think that they do not need help from universities or national laboratories to do the R&D necessary for their future products. We were very much surprised that the contact between an ISTEAC researcher and his company was so small. Nevertheless the companies contributing to ISTEAC represent 50% of the Japanese GNP. While many companies are skeptical about the value of ISTEAC to their own operation, they consider their payments to ISTEAC as a tax for basic research that should be done in Japan, and perhaps a consortium mode is the best way to get the job done.

During our visit to ISTEAC we were asked by the Japanese to explain the MIT-LL-IBM-AT&T consortium. The Japanese can't understand the management structure of the MIT-LL-IBM-AT&T consortium, especially how a researcher in one company can be managed by a manager at another location, and in another company. This may indeed be a problem for the U.S. experiment.

The Japanese experiment (ISTEAC) also has potential problems. The expectations for the commercial exploitation of the high- T_c materials is great. What if no significant applications come within 10 years? The companies within the consortium represent a significant part of the Japanese industrial enterprise, representing half of the industrial GNP of Japan.

MITI is very powerful and can get companies to rally behind this ministry. The bureaucracy in Japan on the MITI level is high powered. We don't have anything like MITI in the U.S.

Of all the Japanese companies, it is the Electric Power Companies that are the most enthusiastic about ISTEAC. Tanaka sees many applications ahead for high field magnets operating at 77 K, especially the Maglev applications. Some other examples include an apparatus to enhance the growing of crystals

by limiting the connection through reduction of eddy current issues and SEMs for identifying strains and other distributed defects in materials. Because of major differences in our population distributions, levitated trains don't make much sense in the U.S. but they do in Japan, so Maglev should be developed there.

ISTEC--Nagoya

M.S. Dresselhaus

The morning of June 7 was devoted to a visit to ISTEC Nagoya. Members of the JTEC team in attendance for the visit included M.S. Dresselhaus, R. Dynes, M.B. Maple, J.K. Hulm, P.M. Horn, R. Quinn, and R.W. Ralston and Paul Herer of the NSF. We arrived at the ISTEC Nagoya laboratory on time and were greeted by Dr. Izumi Hirabayashi, our host for the visit. Dr. Hirabayashi is the leader of the Nagoya division which consists of himself, 8 researchers from companies and Dr. Hatsumi Mori (a visiting scholar) who was finishing her Ph.D. at ISSP with Professor Saite in organic superconductors. Dr. Hirabayashi himself got his Ph.D. from ISSP in semiconductor physics and had spent $1\frac{1}{2}$ years at the Max Planck Institute at Stuttgart.

The ISTEC Nagoya division was located in the rented space on the top floor of the Japanese Fine Ceramic Center (JFCC) and was focused on research on high current densities in the oxide superconductors. The laboratory was very new and just getting started, though the people had already been selected and were in place setting up equipment. There seemed to be sufficient space to accommodate the research, and the equipment was all new and of high quality. The use of rented space was to emphasize the finite lifetime of the project. The location of this group in the JFCC building was intended to enhance collaboration with ceramics experts at JFCC, to promote interaction with regional industry and to make use of the excellent characterization equipment and expertise at the JFCC. One of the researchers working on organic superconductors had her synthesis laboratory in a utility area, away from the main activity, presumably to provide space suitable for crystal growth requiring minimum disturbance for a 7 day period.

The visit started with a detailed summary of the ISTEC overall organization, about which we heard more when we visited ISTEC in Tokyo. The reason for siting a division in Nagoya was the long-term tradition of the region in fine ceramics and the heavy density of industrial participants in this area, thereby providing some regional interactions with member companies. The direct interaction between ISTEC Nagoya and industry was not yet well established. Although the ISTEC researchers appeared to be very knowledgeable

about what was going on in the National Laboratories, they had little direct contact with these laboratories, though they were working along similar lines. It seems as if the visiting scientists are the best source of technology transfer between ISTEK and the supporting industrial laboratories. The coordination between ISTEK Nagoya and ISTEK Tokyo took place through weekly visits of Dr. Hirabayashi to Tokyo, by FAX and by electronic-mail. The visits of ISTEK Tokyo people to Nagoya were less frequent. Of the 8 researchers from the companies, 1 had a Ph.D., 2 had MS degrees and the others only had BS degrees. The participating companies included: NGK Insulators, NGK Spark Plugs, Toyota, Chubu Electric Power Company, Hitachi, Showa Electric, and Kawasaki Heavy Industries. It was very interesting to learn that some of the participating companies were low-tech companies, and in areas where we were surprised to find interest in high- T_c superconductivity.

The first presentation was by Mr. Fumio Mizuno from the NGK Spark Plug Company, who was doing studies on flux pinning and weak link properties of oxide superconductors. The work was fundamental and of high quality. It was impressive that a spark plug company would be interested in fundamental work of this caliber. The detailed studies involved the effect of dopants such as silver in affecting flux pinning, and studying the behavior in different magnetic field regimes for weak link Josephson junctions: e.g., $H < H_{c1J}$, $H_{c1J} < H < H_{c2J}$, etc. His measurements thus far were mostly on transport properties. Even though he was only at the MS level, he seemed very knowledgeable about the field and about what was going on elsewhere. He found 2 different types of hysteresis behavior which he explained by differences in magnetic flux in the grains and in the grain boundaries. He showed that doping with selected dopants changed the weak link properties.

The second talk was by Hatsumi Mori, a lady researcher who was completing her Ph.D. thesis with Professor Saito of ISSP. She was well informed on the field and gave us a talk similar to the one we got at ISSP from Saito. She had set up a nice synthesis chamber and was successfully preparing materials. Clearly her work would involve collaborations with researchers at other places, because her work was quite different from that of the main thrust of the Nagoya group.

We left a questionnaire about Japanese involvement in superconductivity research with Dr. Hirabayashi, which he returned the next day by FAX to our hotel in Tokyo. The visit to ISTEK Nagoya was very useful. Our hosts were very gracious and especially helpful.

B.1.4 Miyazaki Maglev Test Site (JR)

J. Hulm

We (John Hulm, George Gamota and Alan Engel) met with Mr. Keizo Takeda, Chief of Public Relations of the Railway Technical Research Institute, at Tokyo Haneda Airport. We took an ANA flight from Tokyo to Miyazaki on Kyushu islands, about 90 minutes by air. Mr. Takeda explained that southern Kyushu is the "Florida" of Japan, with many palm trees and flowers, a favorite place for vacationers and honeymooners.

From Miyazaki we took a car north to the Maglev Test Center, about 2 hours by road. The drive along the coast was very beautiful. We stopped for lunch at a very nice restaurant overlooking the sea.

We arrived at the test center at 1 p.m., in time to see MLU002, the latest vehicle, make a test run along the 7 km test track, which is parallel to the shore and also parallel to a one meter gauge JR main line. A delegation of superconducting experts was taking a ride, including Professor S. Tanaka, the director of ISTECC.

All controls for MLU002 are operated from a control building at the end of the track. We toured this building, which contains an elaborate computer control system, as well as laboratories for work on the vehicle and electronics systems.

We also visited the power unit for the vehicle, which is a variable frequency, 3 phase, generator fed from the electricity grid, located about 2 km along the track from the control building. The track itself is elevated on pillars, at an average height of about 6 to 8 meters.

To permit the observation of the MLU002 vehicle at speed, a JR station on the meter gauge line has been equipped with an observation platform on its roof, about 100 meters away from the Maglev track, at about the midpoint of the test track. The test track appears to be straight for 5 km and curved for about 2 km - an emergency section which is seldom used.

Later we took a ride on the MLU 002. On that day they were doing special tests on the "landing gear" of the vehicle, that is the rubber-tired wheels on which the car lands on at low speeds when levitation stops. The nature of the levitation force is that it increases with increasing velocity, as eddy currents are induced in the track coils. Normally the vehicle is started and after a certain velocity is reached (~ 100 km/hr), the wheels are retracted.

On this particular day, they were doing tests on the rubber-tired landing wheels (these were adapted from a high speed fighter plane). Essentially, the wheels were not retracted and the speed was run up to 200 km/hr. With the wheels down, the ride was not very smooth. With the wheels retracted we were told that a peak velocity of 517 km/hr was attained with a smaller vehicle.

We then had a two-hour technical discussion with Dr. Kanichiro Kaminishi, Director of the Maglev Test Center, and Dr. Junji Fujie, the Deputy Director. They gave us a technical description of the whole system (I had some experience with it already). They answered all our questions freely and openly and gave us some technical papers which gave detailed descriptions of the system. Some of this information is covered in the JTEC report.

We particularly asked about the operating experience with the superconducting system. They said that the refrigerators had given more trouble than the coils. I asked if the coil had quenched at speed. They said, yes it had, a few times, but the landing wheels could be dropped immediately upon loss of levitation.

As a result of the discussions and our interest in the superconducting system, I was invited to visit the Railway Technical Research Institute in Tokyo, to view a separate superconducting system being tested there. I did so on June 1, 1989.

B.1.5 National High Energy Physics Laboratory (KEK)

M.S. Dresselhaus

The morning of June 2 was spent visiting KEK, the National Laboratory for High Energy Physics, located in Tsukuba. I went out to KEK with Dr. John Hulm, and we were joined by Dr. N. Kanbe of NTT about half an hour after we arrived at KEK, because he missed the bus at Tokyo Station. He actually arrived about 3 minutes before the departure of the bus, but there were no seats left and they wouldn't allow him to stand.

The first part of our visit to KEK was spent in a briefing in the visitor's conference room by our hosts. The first briefing was by Professor Hironori Hirabayashi on superconducting magnets. Dr. Hirabayashi is the Director of Engineering Research and Scientific Support for KEK and is known internationally for his work on superconducting magnets. The organization of the engineering research and scientific support centers at KEK is of interest in its own right, insofar as the engineering and construction aspects of high energy physics give emphasis and prestige to the support activities in materials and engineering, and they therefore can attract high quality people. A second observation of note is the very close coupling between these engineering and materials people with industry, working very closely with industrial engineers in advancing the state of the art and in developing industrially based applied superconductivity technology.

The use of superconducting magnets by the high energy physics community is sophisticated and extensive, thereby significantly advancing the state of the art of applied superconductivity. The high energy physics community creates

a market for a product that makes high demands on superconducting technology and allows industry to rise on the learning curve to position them for other potential commercial applications. The superconducting magnet group at KEK was impressive in their careful and systematic approach to the engineering of superconducting magnets. Their work on NbTi magnets employed much of the basic know-how developed elsewhere, but by working closely with industry, they were able to improve performance and reliability and to enhance manufacturability. They showed work on the engineering of 10T superconducting magnets for high energy accelerator applications that were state of the art. We also heard of research on the design of superconducting magnets based on new materials, such as Nb₃Sn and other materials, to prepare for the next generation of higher field superconductor magnets. Not only were they interested in producing superconducting magnets for Japanese accelerators, but they were working on engineering designs for advanced accelerators in the United States and Europe. Through their close coupling to the industrial designers and manufacturers, the Japanese feel they can compete for contracts on superconducting magnets for accelerators worldwide, and Japanese manufacturers have been quite successful in winning contracts in competition with manufacturers in the U.S. and Europe. One very interesting thing we learned from this visit was their redesign of the Superconducting Supercollider lattice, with magnet designs that were quite different from those of the Americans. In their presentation they emphasized advantages of their design from the point of view of manufacturability. If the Japanese contribute money to the Superconducting Supercollider (SSC) project in the United States, the Japanese would want a corresponding fraction of the equipment development to occur in Japan, thereby enhancing their technology and creating jobs for Japanese workers.

The second presentation was given by Professor Yuzo Kojima, Head of the Mechanical Engineering Center and leader of the Superconducting RF group. Prof. Kojima told us that he and his group were working on improvement of the performance of the niobium based rf cavities of the high energy accelerators. By improving the Q and the voltage operating range, they have been able to increase the operating energy of their electron-positron collider from 24 GeV in 1986 to 30.4 GeV in January 1989 with plans for 32 – 33 GeV expected by the summer of 1989, by improving the quality of the surface of the superconducting cavity material and by adding additional cavities to the acceleration track. The key to their success in getting very high Q values is their ability to go to high rf fields without field emission. This field emission effect has limited the performance of the superconducting cavities at CERN. Their techniques include attention to the purity of the Nb (they use solid Nb material for their cavities), monitoring the residual resistance ratio and the surface morphology of their niobium material. In their work they use various steps of surface treatment

and polishing and they work in class 100 clean room environments, having the appearance of a semiconductor laboratory, with workers in white suits, masks, booties, etc. The level of cleanliness of the laboratories, the quality of the workmanship of the parts, the lovely appearance of the welds, all contribute to the quality of the product and the pride of the workmen.

After the presentations, we had a very efficient tour of the laboratories. The Japanese were very open, showed us everything we asked to see, and were perfect hosts in every way. On the tours we visited 3 or 4 widely separated locations, including the photon factory, the name given to the Japanese national synchrotron radiation facility. The photon factory had many people working on the research floor, though the work seemed significantly less intensive than my impressions from past visits to Brookhaven and SLAC in the United States. I heard that once the high energy experiments at KEK were finished and their high energy physics activities moved into a higher energy range at another location (probably in the U.S. or Europe because of the lack of availability and high cost of land in Japan and because of national priorities), the present KEK accelerator might be converted to a 10 GeV synchrotron radiation source, which could then be fully competitive or superior to the next generation of machines now in the design stage in other countries. About 10% of the synchrotron radiation facilities users were from industry, and most of the work they were doing was in x-ray lithography and surface science. We heard also of a consortium of 22 Japanese companies working with KEK to develop a small synchrotron radiation machine for application to lithography at the $0.2\mu\text{m}$ scale for use by the semiconductor industry. This consortium has built a working machine based on conventional magnets, while NTT (in collaboration with Hitachi) has produced a working machine using a superconducting magnet, resulting in smaller size for the equipment. With a cost of \$200 M for the R&D for the NTT machine, one might question whether this could be of commercial use by the semiconductor industry. I got the impression that the KEK people feel that as they proceed up the learning curve, the machine may become smaller and more efficient. Having this technology (though expensive), may lead to further dominance of Japan in the electronics field, and that seems to be the direction along which they are deliberately heading.

In the U.S. there are also efforts to produce such a small size synchrotron, first in the national laboratories, and second by IBM. It is my impression that the national laboratory program in the U.S. is far behind that of KEK, while IBM is trying to hang in. At this point it is not clear whether this approach will become the state of the art for the next generation of semiconductor electronics, or whether some totally new (not as yet known) technology will surface in time for use for the next generation semiconductor electronics. At any rate, if the table-top synchrotron radiation machine should become the technology

of choice, superconducting magnets could become more interesting as a commercial product. For a variety of reasons, the U.S. has in the last decade lost its leadership position in the field of superconducting magnets, and also its optimism about the field. It is significant that the U.S. industrial program in superconducting magnets has not had the continuity of R&D and manufacturing projects that the Japanese companies have enjoyed.

B.1.6 National Institute for Research in Inorganic Materials (NIRIM)

Rod K. Quinn

In the morning of 6/6/89, Brian Maple and Rod Quinn visited the National Institute for Research in Inorganic Materials (NIRIM). We were hosted by Dr. Zenzaburo Inoue. Dr. Inoue was very enthusiastic about our visit but the remainder of the contingent was more reticent. We were escorted to Dr. Nubuo Setaka the Director of NIRIM who is famous for his work on diamond synthesis. Dr. Setaka graciously received us and visited with us for 10 minutes. We were shown an overview videotape of NIRIM, including purpose, funding and technical highlights.

NIRIM is primarily a solid state chemistry laboratory which specializes in synthesis, structure and microstructure of inorganic materials. In Japan inorganic materials translates primarily into ceramics. NIRIM is organized around a core group concept with each group having some technical project goal. When the goal of the project is achieved members are absorbed into other groups. The atmosphere seems very relaxed with no enduring institutional themes.

Their high temperature superconductivity effort is part of the Science and Technology Agency Multi Core Project, and consists of three core research groups, under Dr. Yoshio Ishizawa. Researchers at NIRIM have an active program for synthesizing and characterizing oxide superconductors. The effort has been particularly successful in determining the crystal structures of the rare earth-"123" and Bi- and Tl- based oxide superconductors. For example, the crystal structure of $\text{TmBa}_2\text{Cu}_3\text{O}_{7-\delta}$ was derived from Rietveld analysis of x-ray diffraction data by Izumi et al. [52] The Rietveld analysis program which was written by F. Izumi was subsequently made available to researchers throughout Japan. Another important recent development at NIRIM was the discovery of superconductivity with $T_c > 20\text{K}$ in the T^* -phase compounds of the type $\text{Nd}_{2-x-z}\text{Ce}_z\text{Sr}_x\text{CuO}_{4-y}$. These compounds are p-type superconductors which are related structurally to the T-phase p-type superconductors of the type $\text{La}_{2-x}\text{M}_x\text{CuO}_{4-y}$ ($\text{M}=\text{Ca},\text{Ba},\text{Sr},\text{Na}$) and the new t-phase n-type supercon-

ductors $\text{Nd}_{2-x}\text{Ce}_x\text{CuO}_{4-y}$. Early photoelectron spectroscopy experiments by researchers at NIRIM revealed the importance of electron correlations in the high- T_c copper oxide metals. After presenting an overview of their program Dr. Ishizawa introduced the project leaders for each core research group and we were briefed by each.

Dr. Bin Okai discussed the group effort in research for new superconductivity materials. He apologized for the lack of results and stated that this effort had not yet gotten started. On the other hand, the group had independently prepared and characterized the $\text{ReBa}_2\text{Cu}_3\text{O}_7$ and the Bi quaternary phases.

Dr. Shigeyuki Kimura leads a team of 6 researchers in a single crystal core group. They are growing single crystals of Bi and Nd superconducting oxides by the floating zone method. They have no atmosphere control on their high temperature furnace thus far but this equipment is coming.

Dr. Shigeo Horiuchi, head of the structure research core group, described the most impressive work. They are looking at structure and microstructure by x-ray diffraction, neutron diffraction and ultra high resolution electron microscopy. Dr. Horiuchi described some very nice work on the effect of substitutional F doping for oxygen in BSCCO that raised T_c from 110K to 113K. A new microscope with 1Å resolution will soon be installed in a new building and will be used for these structural studies. A lot of the initial structure of the superconducting oxides was done at NIRIM. Dr. Horiuchi discussed their work on developing structural models and computer simulation of HRTEM images for structure elucidation. A model for the modulated crystal structure in Bi-Sr-Ca-Cu-O superconductors has been developed from HRTEM images. This work is very highly regarded in Japan and the U.S.

B.1.7 National Research Institute for Metals (NRIM)

M.S. Dresselhaus

We (John Hulm, Rod Quinn, Brian Maple, Paul Herer and Mildred Dresselhaus) arrived at NRIM promptly after lunch. On arrival, we were greeted by 5 members of the Laboratory. Most of the briefings were by Dr. Keiichi Ogawa, Research Director of the Surface and Interface Division, Dr. K. Nakamura, and others. Dr. Ogawa gave us an overview of the NRIM laboratory which was established in 1956 as a research organization under the Science and Technology Agency (STA). The particular interests of NRIM are in (i) advanced materials, rare metals, intermetallic compounds, synthetic materials with special ordering; (ii) reliability of structural materials. In these areas NRIM is expected to conduct exploratory R&D of new materials, to work as a core research institute for national projects, and to work jointly with industry and universities.

The growth of the laboratory has been steady (about 4%/yr in budget), but over the past 20 years there has been a slight decrease in personnel, and this decrease has been taken in administrative and support staff. We heard that a 4% decrease in personnel would take place in all the national laboratories this year, at NRIM and other similar laboratories, and in fact also in universities. Right now the activities of NRIM were taking place at two locations: Tsukuba and Meguro. Soon the Meguro operation which was more than 3 times larger in laboratory floor space would be moving out to Tsukuba, with many new buildings to be constructed on the Tsukuba campus. Of the approximately 450 people (about 350 scientific people) at NRIM, about 20 researchers were involved in superconductivity research. The number of researchers at NRIM can be supplemented by visitors and students, but these are quite few in number. With the advent of high- T_c superconductivity, there was an increase in budget.

Some of the research foci at NRIM in superconducting materials were summarized for us. Prior to the high- T_c discovery, NRIM was doing pioneering work on a broad range of superconducting materials with a focus on the study of new materials and the properties of multilayer superconducting materials such as Mo/Sb with $T_c \sim 6$ K and the intermetallic compound PdTe with $T_c \sim 7$ K. With the advent of high- T_c materials, NRIM quickly moved into this field and made its mark. For example, Dr. Hiroshi Maeda and his group were the first to prepare Bi-based high- T_c materials. In addition to basic studies, the Bi-Sr-Ca-Cu-Oxide materials are being investigated for wire and thin film applications. Some of the NRIM effort is also directed toward finding new materials with even higher T_c values.

The NRIM superconductivity group is also developing superconducting materials for use in high field superconducting magnets. This is a leading laboratory in the development of Nb_3Al , and $Nb_3(Al-Ge)$ materials for magnets, including the development of multifilamentary wire conductors based on these materials. The NRIM researchers work with the various superconducting wire companies in Japan to develop wire suitable for use in high field steady state magnets (up to 20 tesla), and in pulsed field applications up to 80 tesla. The NRIM group has the experience and resources to build test magnets of various types and designs.

NRIM is part of a "Multi-Core Research Program on Superconducting Materials" set up by the Science and Technology Agency (STA) in 1988 to promote activities among industry, academia, and government with responsibilities in 6 areas:

1. theoretical research on the electronic structure and mechanism of superconductivity in new superconducting materials by computer simulations,

2. development of a data base for R&D in superconducting materials,
3. purification of reactive elements and fabrication of raw powder materials with controlled structure for the new oxide superconductors,
4. development of fabrication technologies for thin films possessing high- T_c and high- J_c ,
5. development of fabrication technologies for new superconducting wires and tapes by laser beam sputtering, rf sputtering etc.
6. design and development of high field magnets, including a 80 tesla, long (10 msec) pulse magnet, a 40T hybrid magnet in collaboration with the Francis Bitter National Magnet Laboratory at MIT and other institutions, and a 20 T large bore superconducting magnet.

The NRIM laboratory is especially active in the development of new superconducting materials using the high field magnets. In the development of new superconducting materials and high field magnets, their collaborations are worldwide (Karlsruhe, Grenoble, MIT, University of Iowa, University of Alabama). The NRIM laboratory also had close contacts with the NRIM laboratory, another STA sponsored laboratory, that was located nearby, and specialized in structural studies.

With regard to R&D on high- T_c materials, Dr. Kazumasa Togano showed us outstanding work on high- T_c wires using a variety of approaches, including cold rolling to get alignment of the superconducting grains and the use of ultrasonics in processing to break down grain boundaries.

With regard to their R&D program on low- T_c superconducting materials, they were actively engaged in achieving further advances with the filamentary magnet wire. In this work, they had collaborated with 5 companies and hope to commercialize new products within 3 years: Kobe Iron and Steel, Furukawa, Sumitomo Electric, Showa Wire and Cable, and Hitachi.

Following the presentations, we had a tour of the laboratories where we saw them working on wire development and prototype magnet development. We were impressed by the excellent facilities, the level of the work and by its broad coverage. The surface group also had an excellent collection of characterization instruments.

In the thin film portion of the NRIM effort, they were making modulated structures by Bi(Pb)SCCO, utilizing the large periodic strain field that is induced. As in other laboratories, the NRIM researchers were working on the phase diagram of the BiPbSCCO compound to grow the high- T_c phase predominantly. They were also introducing Pb and other dopants for pinning the vortices in BSCCO. As part of their film work, they were making artificially

layered high- T_c materials using magnetron sputtering, and the reactive plasma vapor deposition technique.

B.1.8 Railway Technical Research Institute (RTRI)

J. Hulm

I went to RTRI alone, as an outcome of the visit to the Maglev test site on May 30, 1989. RTRI is the Central R&D Laboratories of the entire Japan Railway system. It is a large site with many buildings, and probably with at least 1,000 people. Entirely devoted to development work on trains, track, controls, repairs and human factors, there is no equivalent in the U.S., but the Western European countries have similar laboratories.

At RTRI, I met Keizo Takeda and Junji Fujie (from Miyazaki) and was introduced to the President of RTRI, Dr. Masanore Ozeki who accompanied me on a tour of the main laboratories. We visited the dynamics testing laboratory for Shinkansen type vehicles, where the units remain stationary while the wheels are driven by rollers under the train. This test unit investigates the dynamics of various types of Bogie units and vibration problems connected with high speed operation. This laboratory is part of the system tests for the planned Bullet train speed-up which is targeted at about 300 km/hr.

Next we visited the Maglev test laboratory and saw a Bogie with 6 superconducting magnets and 2 refrigerators. The refrigeration systems were running, obviously on life test.

I saw one of the magnet coils on another test bench. The conductor is Nb-Ti stabilized with copper in about a 1 to 1 ratio and the filaments are 23 micron in diameter. The cable has 2300 strands of conductor formed into a 2mm \times 1 mm cable. Several Japanese suppliers were utilized, but no foreigners.

The magnet was built as a race-track, 1.8 meters long, 50 cm high and 25 cm wide. It consisted of 1,167 turns and the normal exciting current was 600 amperes. The magnet was potted in Epoxy and operated at 4.3K. The magnet was normally run up at about 10 amperes/sec. The maximum design current was 800 amperes.

The magnet has been deliberately quenched several times, without harm. It has also quenched at 600 amperes during vehicle tests for unknown reasons. The energy release is about 500 KJ, which causes a temperature rise of about 100K.

The cryogenic system consists of closed-cycle refrigerator above the 3 coils (on one side of the Bogie) and a 40 liter helium tank on board.

Apparently, the cryogenics for cool down is supplied by external liquid initially. They said that liquid N_2 is pumped in to bring the system to 77K.

Subsequently, an external Toyota liquifier pumps in cold gas to bring the system to 4.3K. (It amazes me, but every company in Japan seems capable of supplying its own design of helium liquifier!) The Toyota liquifier is then disconnected and the on board refrigerators (Toshiba, Mitsubishi) take over the 5 watt cooling supply to the three magnets.

There is an on board liquid N₂ tank which provides the shield cooling for the cryostats.

MLU002 has operated over about 10,000 kilometers to date (about 1,000 trips on the test-line). The magnets quenched a few times in service — they could not yet identify the cause in all cases. Generally, the cryogenic systems have given more trouble than the magnet coils.

We had a short tour of the materials testing laboratory, the acoustic laboratory and we saw test work on standard meter gauge vehicles.

I was taken to lunch at a very nice French restaurant in Kunitachi. The area is very pretty, apparently there is a small University nearby. The boulevard was unusually wide and lined with trees. There were many bookshops, cafés and students on bicycles.

The lunch extended into midafternoon and we had a wide ranging discussion on economics, technology, etc. President Ozeki has served as a Japanese delegate to several UN and International conferences, and his International knowledge was extensive.

As far as Maglev is concerned, Ozeki said that they had made good progress, but that they were competing with 150 years of technological experience in steel wheel trains and much remained to be done before Maglev could be developed as a full-scale system. Important items included the problems of switches between different tracks, electrodynamic drag at low speeds, provision of on board power, and the aerodynamic of tunnels at 500+ km/hr.

This visit was very informative and President Ozeki seemed pleased at my interest in RTRI. Since I have been a railroad enthusiast all my life and have previously spent time at the Derby laboratories of British Rail, it was a wonderful opportunity to observe a superb modern engineering facility devoted to trains.

B.2 Universities

B.2.1 Institute for Solid State Physics – University of Tokyo

M.S. Dresselhaus

Since the Institute for Solid State Physics (ISSP) is one of the leading institutes for the study of superconductivity, all members of the JTEC team visited ISSP. Because of our interest in the high magnetic field facility, a tour of the high magnetic field facility was orchestrated. The tour was led by Professor Miura, who is the originator and guiding force behind the high field facility. All members of the JTEC team were impressed by the world class megagauss facility. With regard to research on high- T_c superconductors, the availability of the highest magnetic fields in the world for research purposes provided ISSP researchers the opportunity for exploration of the $H_{c2}(T)$ curves over the entire range of temperature.

The megagauss laboratory at the ISSP allows study of solid state phenomena in the megagauss range, where various new phenomena are expected to occur. For the case of high- T_c superconductivity, this facility permits study of the magnetic phase diagram for the high T_c superconductors, as mentioned above. At the Megagauss Laboratory, pulsed high magnetic fields are generated by three different techniques: electromagnetic flux compression, a single turn coil technique, and long pulse non-destructive magnets at somewhat lower fields. The long pulse non-destructive magnets are set up in a user facility, with experimental set-ups for doing optical, transport and other measurements. Special equipment is also provided to carry out measurements on the time scale appropriate to the available pulses. The truly state of the art research is carried out in the megagauss facility using the single coil or electromagnetic flux compression method. With the single coil method, there is a reasonable probability to save the sample for multiple measurements in megagauss fields on the same sample.

Following the magnet laboratory tour, we started the formal program on superconductivity research at ISSP. Professor Fukuyama was our host and master of ceremonies. He first introduced us all to Professor Toru Moriya, the Director of ISSP, who earned an international reputation for his theoretical studies of magnetism.

Professor Fukuyama then explained the organization of superconductivity research at ISSP. Superconductivity has been an area of science priority in Japan for some time. Starting in 1984, a 3 year project on New Superconducting Materials was initiated (1984-87), and with the advent of High- T_c

Superconductivity, this project was extended to 1988 under the heading High Temperature Oxide Superconductors. Superconductivity studies are presently funded under the heading "Mechanism of Superconductivity" for the 1988-91 period. The transfer of information among the researchers is enhanced by a "New Materials Forum" at ISSP which meets twice monthly to communicate up-to-date information in superconductivity research.

The overview presentation by Professor Fukuyama was followed by detailed presentations from several researchers. The first was given by Professor Y. Iye, who spoke about transport properties on single crystals. The research focused on anisotropy phenomena, anisotropy measurements at high fields, pressure dependence of T_c , flux creep effects, angular dependent phenomena etc. This was world class fundamental research.

The second presentation was by Professor N. Miura, describing magnetization measurements to study hysteresis phenomena and $H_{c2}(T)$ over the entire temperature range. The availability of megagauss fields allowed measurement of $H_{c2}^{\parallel}(0) = 40 \pm 5\text{T}$ and $H_{c2}^{\perp}(0) = 110 \pm 10\text{T}$ giving coherence lengths of $\xi_{ab} = 30\text{\AA}$ and $\xi_c = 10\text{\AA}$. These anisotropy values are in good agreement with those obtained elsewhere, such as the IBM group, who have come up with an anisotropy factor of 4.

The next presentation was given by Professor H. Yasuoka on NMR studies of high- T_c superconductors. The presentation covered measurements of NQR to probe the homogeneity of oxygen in the plane, and NMR measurements of anisotropy of the Knight shift, and temperature dependence of T_1 . The unusual properties of the $1/T_1$ behavior in the normal state was emphasized. Superconductors were found to have very high- $1/T_1$ values while non-superconductors had low $1/T_1$ values. This NMR work also was world class research.

The next presentation was by Professor M. Tsahikawa who spoke on materials preparation and characterization. Particular emphasis was given to the temperature dependence of the specific heat, with comments that the jump in C/T at T_c was a good characterization method for sample quality in addition to x-ray, susceptibility and resistivity measurements.

This was followed by a presentation by Professor H. Takei who was working on new oxide materials (e.g., $\text{Na}_x\text{Ti}_y\text{O}_z$) with potentially interesting superconducting properties. The structure and normal state properties of this class of materials was described. Another aspect of work in his group was the preparation of thin film materials. He described the preparation of BSCCO films by a new solvent evaporation epitaxy (SEE) method. In this method the ingredients were used with KCl as a plasticizer and an organic liquid which was then applied to a substrate (e.g., single crystal MgO), then heated to 100°C to dry the material and drive off solvent. Subsequent heating to $\sim 915^\circ\text{C}$ drove off the KCl, leaving a single crystal film on the substrate. This method allowed

growth of films in oxygen, and air, with a rapid growth rate. The method was simple, allowed preparation of large area samples showing sharp transitions at $\sim 80\text{K}$ with $\rho \sim 300\mu\text{cm}$ at T_c . Measurements of J_c on these thin films had not yet been made.

The final talk was given by Professor G. Saito on organic superconductors. This was an extremely interesting talk. Organic superconductors are produced by suppressing the Peierls transition. The BEDT-TTF system was presently the highest T_c organic superconductor system with $T_c \sim 10.4\text{K}$. Leading work in this field has been done in the USSR, Japan, U.S., and France. Professor Saito showed us a large number of measurements on H_{c2} , anisotropy studies, isotope effect, tunneling, thermopower, NMR among others. Many of the normal state and superconducting properties were strange. This looks like a field of significant interest for further work. Professor Saito is an international leader in this field.

Because of our next commitment which was a lunch meeting as the guests of Mr. Chiba, head of the ERATO program, this most interesting visit to ISSP was concluded in haste. We saw many world-class efforts here, carried out by relatively few people who were very talented, were working very hard, and had enough support to make progress. Researchers at ISSP may have reasonably good continuity in their support, and they have a high degree of recognition as professors of the University of Tokyo system.

B.2.2 Tohoku University

M.S. Dresselhaus

A visit to Tohoku University in Sendai was organized in connection with our high- T_c Superconductivity JTEC study because it is one of the main university centers in Japan for basic studies in superconductivity. The major part of the superconductivity studies at Tohoku University are carried out in the Institute for Materials Research, with an additional strong effort taking place in the academic departments of the university located on the hill about 1 km away. The interactions between the researchers at the Institute for Materials Research and at the academic departments are strong.

The Institute for Materials Research is of historical interest to Japan in its own right, as the first Research Institute that was established in connection with a National University. The Institute was initiated in 1916 and was inaugurated in 1919 as the Iron and Steel Research Institute, reflecting the early focus of its founder and director, Professor Kotaro Honda, who was a pioneer in the development of KS magnet steel, leading to the highest field magnets of that time. In 1922, the research activities were extended to non-ferrous metals and

alloys, and the Institute was renamed the Research Institute for Iron, Steel and Other Metals. The Institute continued under this name until 1987 when it was reorganized and renamed the Institute for Materials Research, reflecting the broader interest of the researchers and the progress of materials science internationally during the intervening years. Interestingly, the first research institute building was funded by the generosity of the Sumitomo family, and the recent building (containing a small portion of the original building for the sense of history) was also funded by private sources, though government funds were used to instrument the renovated laboratory.

In 1981, the High Field Laboratory for Superconducting Materials was established and the laboratory is now the Japanese National laboratory for steady high magnetic field research. The activities of the Institute and the High Field Facility are open to researchers from all Japan and also from abroad.

The research organization of the Institute for Materials Research is divided into four divisions: Materials Property Division, Materials Design Division, Materials Development Division, and finally the Materials Processing and Characterization Division, in addition to three special research facilities, the Irradiation Experimental Facilities, the High Field Laboratory for Superconducting Materials mentioned above, and the Facility for Developmental Research of Advanced Materials. The faculty organization bears some resemblance to the German system, whereby each Full Professor will have under him an associate professor and one to three research associates in addition to several graduate students and a few senior undergraduates. Thus a position at the Institute for Materials Research is regarded as a very good position in Japan. The Institute staff consists of 350, including 60 faculty members and 100 research associates, 50 visiting researchers including 10 from abroad. In addition to the 350 staff people at the Institute for Materials Research there were about 100 graduate students with about $\frac{2}{3}$ leaving after an MS degree and $\frac{1}{3}$ completing the Ph.D. degree. In addition, there were about 50 industrial researchers working on "papers Ph.D. degrees" with faculty at the Institute for Materials Research. All in all, there are 26 research groups each having a little more than 10 researchers. They estimated that there were 100 people working on superconductivity at Sendai, a little more than half associated with the Institute for Materials Research.

Our main host for the visit was Professor Yoshio Muto, who heads up a large national program in superconductivity and also a large program at Sendai. In addition, our main hosts were Professor Masashi Tachiki (solid state theory), Prof. Yasuhiko Syono (chemistry), Prof. Tetsuo Fukase (experimental physics), and Prof. Norio Kobayashi (experimental physics). We were also welcomed by Prof. Masumoto, Director of the Institute for Materials Research and we signed his visitors book.

The morning of June 3, 1989 was initially unscheduled. Since the JTEC panel members (Dynes, Ralston, Gallagher, Dresselhaus, Hulm) were anxious to utilize this opportunity to see more of the research activities at Sendai, Dr. Nobuyuki Kambe of NTT helped us arrange a laboratory tour of the Institute for Materials Research and their magnet laboratory facility. Dr. Kazuo Watanabe, who knew a great deal about the magnet laboratory, graciously showed us around, and he explained a lot of details about the magnets, the experiments in progress, and the research environment of the facility. We owe him a debt of gratitude for dropping his scheduled work for the morning to show us around. Basically the high magnetic field facility has a number of Bitter magnets available for high field research, and is in many ways similar to the Francis Bitter National Magnet Laboratory (FBNML) at MIT, though the variety of magnets that are available is not quite so extensive as at the FBNML. In addition, the magnet laboratory at Sendai has available a variety of superconducting magnets, including three hybrid magnets consisting of inner polyhelix sections and outer superconducting sections. The largest of the three is a world class magnet providing steady magnetic fields in the 29-31 tesla range, approximately equal in performance to the hybrid magnet at the FBNML at MIT and the one at Grenoble in France. This magnet can however be used only about six days a month, because of the cooling requirements of the superconducting coils and the need to warm up the magnet and to dry it out before the next series of operations. We were told that this limitation on the length of available time on the hybrid magnet did not create major problems to users of the facility.

Magnet development R&D at Sendai and at the FBNML had some significant differences. Whereas the Americans designed and were involved in detail with the construction of the magnets, the Japanese were involved only with the initial design and with the construction of a prototype. The Japanese then contracted out to industry for the preparation of the superconducting magnet materials (Furukawa) and for the scale-up and construction of the actual magnets (Hitachi, Toshiba). Thus, Japanese industry took over on the details of the scale-up, the mechanical design, consideration of the stresses, loads, mounting, etc, thereby transferring significant experience, knowhow, and technology to Japanese industry, especially in the area of superconducting magnet design.

After the visit to the magnet laboratory, we returned to the conference room at the Institute for Materials Research where we heard presentations of research activities at the magnet laboratory and elsewhere on campus on superconductivity research. The morning session was mostly devoted to discussions of materials science issues and the dependence of the resistivity vs. temperature on a $\log \rho$ vs. $(1/T)$ scale, measuring activation energies for various magnetic field orientations, including both $\vec{H} \parallel \hat{c}$ and $\vec{H} \perp \hat{c}$. We also heard presentations on the time dependence of the magnetization and the relation of this work to

flux pinning and flux creep.

The scientific discussions were interrupted to gather for lunch and to meet the Director of the Institute for Materials Research. As mentioned above, we all visited Professor Tsuyoshi Masumoto, exchanged greetings and signed his book, after which we went off to lunch. The lunch was hosted by the Americans and took place in a first class French restaurant, with the 5 Japanese hosts in attendance. In the evening the Japanese hosted a fancy dinner party for the American visitors in a traditional Japanese restaurant. The social aspects of Japanese hospitality still remain an important element in strengthening U.S.-Japanese ties with long time friends and colleagues. During lunch we got into a discussion on the growth of single crystals, and learned that theorists at Sendai (and also elsewhere) were enlisted into the growth of single crystals because of the shortage of people and the need for good materials. We learned that Japanese theorists seem to have talent for growing single crystals of various classes of materials, e.g., YBaCuO.

Returning to the laboratory after a very heavy lunch meal, we continued discussions on basic superconductivity research in Japan. The first part of our discussion focused on organizational issues. We heard that about 100 people in Sendai were working on superconductivity. While the cooperation within the Institute for Materials Research was very good and the cooperation was also strong to the academic departments, there had not been much cooperation with people outside Sendai in the past. We were told that this was now changing, and that collaborative research with three industrial laboratories was in progress (NEC, NKK and Casio). With regard to the High Field Facility, $\frac{2}{3}$ of the research work was on superconductivity, much higher than the ratio at FBNML. Within the superconductivity program, more than $\frac{2}{3}$ was directed toward high- T_c superconductivity and less than $\frac{1}{3}$ toward conventional superconductors. We then attempted to come up with comparable metrics for the superconductivity effort in Japan and the U.S.; after some discussion, we concluded that it was very difficult to make the comparisons in terms of budget figures, because the budgets were arranged so differently with regard to cost for salaries, facilities, usage, etc. However, a comparison of level of effort seemed more appropriate. After some discussion, they came up with the following table of superconductivity personnel, estimated at 500 researchers plus 300 students in Japan, geographically distributed as follows.

Hokkaido	3%
Sendai	20%
Tsukuba	5%
Tokyo	30%
Kyoto and Osaka	25%
Okazaki and Nagoya	10%
Hiroshima and Fukuoka	7%

We decided to try the same exercise with researchers in Tokyo to see if we could come to some agreement. We heard that the advent of high- T_c superconductivity received a rapid response from the research community with major shifts in effort, and a corresponding reduction in activity in other fields. Additional funding was however provided to make the transition rapid and efficient. We heard that there was little complaint in Japan about budgetary reprogramming during the change in the directions of the superconductivity research community.

Following this lengthy discussion on research organization of the Japanese superconductivity program, we returned to scientific discussion on superconductivity. We heard a presentation by Professor Syono on systematic studies of the Tl compounds regarding the relation between T_c , and the number of CuO_2 layers, the stoichiometry of divalent and trivalent species, and the relation between T_c and the Hall constant. Professor Syono presented results based on both the Tl_1 and Tl_2 systems, representing very careful and very beautiful materials work keeping the number of Tl layers constant. From this came estimates of the correlation energy $U \sim 7\text{eV}$ and the hopping energy $t \sim 1\text{eV}$. This work showed that increase of the number of CuO_2 layers increased T_c at first, but after about 3 or 4 layers the maximum $T_c \sim 110\text{K}$ was reached, consistent with their measurements of the in-plane lattice constant, showing a maximum hole concentration in the CuO_2 layers at about 4 CuO_2 layers. In related work, Dr. Koike showed that the substitution of Lu for Ca in the Bi compounds reduced T_c at first, and then led to a superconductor-semiconductor transition with our going through a non-superconducting metallic phase. This was followed by a presentation by Dr. Watanabe on high magnetic field studies ($H \parallel \hat{c}$ axis and $H \perp \hat{c}$ axis) of critical current densities vs. magnetic field. Some of the highest current densities reported in a magnetic field were obtained by this group. In these presentations we also saw some of the most beautiful high resolution work, that we saw anywhere, led by Professor Kenji Hiraga working on a JEOL 400 keV TEM, housed in an old building. The institute for Materials Research also has a 1MeV high resolution TEM, but the researchers seemed to favor working on the 400 keV instrument.

Finally Professor Tachiki presented a model for strong vortex pinning which was developed to explain the effect of anisotropy on pinning and to explain

pinning effects for small superconducting coherence lengths. Although the researchers at Sendai did not seem to interact strongly with researchers at other institutes, there were strong interactions and good collaborations going on between workers at Sendai. This interaction contributed importantly to the high quality of the research.

B.2.3 University of Tokyo, Faculty of Engineering

M.S. Dresselhaus

After spending the morning at the Institute for Solid State Physics (ISSP) in Roppongi, and having lunch with Mr. Chiba on the ERATO program, the entire JTEC team took the subway to Tokyo University and walked from the train station to the Industrial Chemistry Building where Professor Kitazawa was located. Compared to industrial laboratories, the University laboratories are old and dingy. But compared to most university buildings that I have seen in Japan, the building where the Industrial Chemistry Department was located was among the better-looking buildings.

Our discussions started with a presentation by Professor Kitazawa on how he got into high- T_c superconductivity research. In 1984, Professor Shoji Tanaka had the idea to start a special program in Japan to look for new superconducting materials, with an intention to discover some higher T_c materials. To carry out this project he asked Professor Kazuo Fueki and Dr. Koichi Kitazawa to join him in a special program on oxide superconducting materials. There had in fact been activity on oxide superconductors in the University of Tokyo Engineering School since 1976, but in 1984 new resources were brought to bear on this program. The activities of the special program focused intensively on the study of $\text{Ba}(\text{Pb,Bi})\text{O}_3$ compounds, their synthesis, characterization and properties measurements, including transport properties (resistivity, Hall effect, Seebeck effect), specific heat (to measure the electron density of states at the Fermi level and the Debye temperature), optical properties (to determine the plasma frequency, phonon modes by IR and Raman spectroscopy, interband transitions, ultraviolet spectra), tunneling spectroscopy, neutron scattering and structure determination. The $\text{Ba}(\text{Pb,Bi})\text{O}_3$ compounds had unusual normal state properties, including a low carrier density ($\sim 10^{21}/\text{cm}^3$), showed charge density wave behavior, showed insulating behavior with a transition to a metallic phase by doping, and superconductivity was observed in the metallic phase.

As it turned out, the funding for the oxide program was coming to an end, and the group was celebrating the completion of the program with mixed emotions, since in the three year period of the grant no material has been found with direct promise for increased high- T_c above that for Nb_3Ge which at that

time held the record at 23.2K. This was also the time close to the retirement of Professor Tanaka and Professor Fueki, and there were thoughts of succession to the next generation of researchers. At the celebration party, a lady professor Kazuko Sekizawa of Nihon University asked Prof. Kitazawa if he had read the paper by Bednorz and Müller, and whether he believed in their results. Kitazawa had not heard of this paper but did remember this interchange after the party was over. He subsequently gave the follow-up assignment to one of his students, who not only studied the Bednorz-Müller paper but tried to repeat the synthesis of their material. Because of their extensive experience in this field, the Kitazawa-Tanaka group was in an excellent position to prepare these ceramic oxide materials, characterize them, and carry out property measurements. And thus it happened that when the MRS December 1986 meeting took place, this group had a large amount of data to present, convincingly demonstrating that a new family of high- T_c superconducting materials had been discovered. The convincing verification of the Bednorz-Müller result was a very important achievement, because a number of so-called high- T_c superconducting materials had been announced over the years, but the results were never reproducible until the Kitazawa announcement at the MRS December 1986 meeting of the cuprate ceramic materials.

The first formal presentation to the JTEC team was given by Professor Kitazawa, and it was indeed an excellent presentation. He first summarized the impressive achievement of this small research group, including their identification of the superconducting phase La-Ba-Cu-O, their discovery of the $(\text{La, Sr})_2\text{CuO}_4$ and $(\text{La, Ca})_2\text{CuO}_4$ materials, their studies of hole doping in the low carrier density doped phase, studies of the strong anisotropy of the electronic and superconducting properties, the identification of CuO_2 as the conduction layer, the high- H_{c2} values, the sensitivity of the material to H_2O contamination, the effect of non-magnetic dopants (such as Zn and Li), the relation between the plasma frequency, the hole concentration and the critical temperature, the phonon density of states, the anomalous Seebeck effect, the effect of oxygen non-stoichiometry on the electronic and superconducting properties, thin film processing by sputtering and sol-gel (alkoxide) methods, synthesis of the $\text{Ba}_2\text{LnCu}_3\text{O}_{7-\delta}$ materials as $T_c \sim 90\text{K}$ superconductors (where Ln denotes a lanthanide), the discovery of electron-doped superconducting $(\text{Nd, Ce})_2\text{CuO}_4$ materials, the symmetry between electron-doped and hole-doped superconductivity, the superconducting gap measurement by scanning tunneling spectroscopy and the study of superconducting fluctuations near T_c .

Professor Kitazawa then went on to describe their present research program, which included several areas, and a wide range of materials: $(\text{La, M})_2\text{CuO}_4$, $\text{Ba}_2\text{LnCu}_3\text{O}_{7-\delta}$, $\text{Bi}_2\text{Sr}_2\text{Ca}_n\text{Cu}_{n+1}\text{O}_y$, electron doped superconductors and new

superconducting materials. Scanning tunneling spectroscopy studies would be continued to characterize surfaces, and would be combined with a newly arrived MBE system to study vortex lines and the superconducting energy gap in situ. The MBE system was also an essential ingredient for their new thin film program. Basic studies on the critical current were in progress with particular emphasis on the pinning of vortex lines in a high magnetic field and the relation of vortex pinning to the microstructure. The Kitazawa group, like many other groups in Japan, were heavily involved with new superconducting materials research, especially in the area of electron-doped superconductors, and the behavior of electron-doped superconducting materials under reducing conditions. Their work on single crystal growth and anisotropy studies based on these single crystals was continuing, with special emphasis on the $(\text{La}_{1-x}\text{Sr}_x)_2\text{CuO}_4$ family for different x values using the flux growth and float zone methods, because of the relative simplicity of the lanthanum cuprate system insofar as it has a single CuO_2 layer. Also under investigation is the superconducting-normal transition in a magnetic field with particular reference to the identification of the mechanism for the broadening of the transition in a magnetic field, addressing flux creep problems, fluctuations, and a model for the transition to a superconducting glass.

Following the presentation by Professor Kitazawa, we heard a presentation by Professor Uchida who is now an Associate Professor in the Engineering Research Institute. Professor Uchida is heavily involved in studying the electron-doped superconductors, with particular emphasis on studying the symmetry between the electron-doped and hole-doped superconductors. He described studies in $(\text{Nd}, \text{CeSr})_2\text{CuO}_4$, an electron-doped superconductor first found by Professor Akimitsu of Aoyama Gakuin University. Professor Uchida and Kitazawa both described world class research work done by undergraduates in their groups; because both Kitazawa and Uchida are young faculty members and not so well established, they do not have so many graduate students and a significant fraction of their research work is done in collaboration with undergraduates.

The experience with the synthesis of electron-doped materials is significantly behind that for the hole-doped materials. Professor Uchida and his students are now trying to prepare single crystals of the electron-doped material and are having difficulty with preparing homogeneous single crystals. For the electron-doped superconductors, reduction, rather than oxidation, is needed to achieve superconducting phases. Much of their work thus far has been on the optical properties, where they have studied free carrier and interband transitions predominantly. Plasma frequencies for electron-doped superconductors ($\omega_p \sim 0.9\text{eV}$) were found to be similar to those for hole-type superconductors (typically $\omega_p \sim 1.1\text{eV}$). Professor Uchida told us that with present materials,

they had difficulty achieving zero resistance at T_c . He also told us that he had difficulty in correlating the Hall coefficient with T_c , but did find that a change in sign in the Hall coefficient as a function of doping level corresponded to $T_c = 0$.

Professor Uchida has also been working on the $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$ system for large x ($0.3 < x < 0.4$) and they have also made sizable samples of $\text{YBa}_2\text{Cu}_3\text{O}_7$ ($2\text{mm} \times 2\text{mm} \times 0.01\text{mm}$) for single crystal studies. He also has an effort in investigating new and exotic superconductors, but have not yet made any interesting new materials that are superconducting.

Following the presentation by Professor Uchida there was a brief discussion of consortia. Our Japanese hosts were especially interested in the newly proposed MIT-LL-IBM-AT&T Bell Consortium, though the ISTEK Consortium and consortia in general were also discussed. Dr. Dynes emphasized that the joint consortium between universities, government laboratories and industry was quite different in concept from ISTEK and said its success would depend to a significant degree on the skill of its management team. Professor Kitazawa did not think that consortia were helpful to industry, but rather were a method for getting industrial contributions for basic research. Professor Fukuyama feels that the present is the time for basic research and strong interactions between people at sites active in superconductivity research. We then went into a panel discussion on opportunities and challenges of high- T_c superconductivity, with R.C. Dynes and M.B. Maple serving as Panel Members from the American side, and K. Kitazawa and H. Fukuyama serving as Panel Members from the Japanese side.

Dr. Kitazawa made several points in his opening statement. He feels that continued attention should be given to research on new superconducting materials, though this research is risky. While the short coherence distance is an interesting problem hampering applications of the high- T_c superconductors, he feels that some increase in T_c is possible, and is hopeful that sufficient advances can be made to allow for applications to the electric power industry. He was somewhat doubtful about applications to the electronics industry, except for SQUID applications. Kitazawa feels that the demonstration of a Josephson switching effect would be needed to signal practical electronics possibilities, and he feels that control of interfaces, grain boundaries, twinning effects, and anisotropy effects are needed for further progress. Perhaps somebody will solve the pinning problem and there will be other technical breakthroughs, but this will take lots of effort and study.

In his statement, Maple emphasized the intellectual challenge and expressed hopes for technological applications. He emphasized materials as an essential ingredient to achieving technological applications, and feels that this is where the present effort should be focused. Maple then spoke to the interdependence

of basic science and technology, with theoretical concepts leading to new experiments which require new materials that lead to further theoretical ideas. He would emphasize two research directions for now. Firstly he recommends that we take presently available materials, and try to solve material problems inhibiting technological applications, such as grain alignment, and flux pinning. Secondly, Maple recommends looking for new materials, new dopants, developing materials to specifically satisfy a set of requirements, correlating desired properties with materials parameters.

By this time Professor Fukuyama had to leave and Professor Iye took his place. Iye stressed basic research and didn't have too much to say about the applications. Iye stressed the similarities of the high T_c superconducting materials to conventional superconductors with regard to their superconducting properties (except for magnitudes of the superconducting coherence distance and the upper critical field values), but stressed the wide differences with regard to their properties in the normal state. He recommended giving attention to that aspect. Iye indicated that the main features of the normal state would be clarified within two years. A great part of the excitement about the new high- T_c materials was in new physics phenomena which would be uncovered with regard to superconducting fluctuations and flux dynamics. Professor Iye also emphasized the importance of looking for new superconducting materials.

The final opening summary was by Dr. Dynes who emphasized the speed at which progress was still being made, and consequently the difficulty in looking into the future. He emphasized the importance of the discovery of the electron-doped superconductors from a theoretical standpoint, and studies made of the anisotropy phenomena, made possible by the increasing availability of good single crystal materials. Dynes feels that flux creep studies should now be emphasized, as well as studies connecting spin fluctuations, magnetism and superconductivity, with a major goal toward identification of the superconductivity mechanism in the high- T_c superconductors. Dynes also feels that a significant effort should be given to studies of the normal state properties, again emphasizing their unique features with regard to temperature dependence of the resistivity, large correlation effects, and unusual Hall effect behavior. He feels that substantial effort should go into understanding the superconducting band gap, whether there is a gap, whether it is anisotropic in k-space, and why optical, tunneling, NMR results do not agree.

The panel discussion was interrupted for a tour of Kitazawa's laboratory. Much of the equipment was homemade and not fancy. The laboratory was extremely crowded, dingy and somewhat decrepit. Recently he had acquired several pieces of commercial equipment which had made a big difference to his operation, including a recently acquired Japanese-made SQUID magnetometer, and a just-delivered MBE machine with capabilities of doing in-situ scanning

tunneling spectroscopy. What was impressive about his laboratory was how much he was able to accomplish with only a few people and not-fancy apparatus. His key to success was incredibly hard work, good organization of his small group of very talented people, and good collaborations with others at the University of Tokyo. Because of Kitazawa's success, there are many demands on his time during the day and many speaking invitations in other locations. To keep his research operation going, he typically returns to the laboratory to work for 4 or more hours after dinner, and then is back again in the morning to deal with other demands.

Following our visit to the laboratory, the JTEC team and the Japanese hosts went to the University of Tokyo Faculty Club for dinner to continue with the panel discussions in a more informal setting. At this dinner party, Professor Kitazawa served as our congenial host.

B.3 Industrial Laboratories

B.3.1 Fujitsu

R.C. Dynes

Fujitsu has two research laboratories, one at Atsugi and one at Kawasaki. They are divided into five divisions titled Electron Devices, Communications, Information Processing, Electronic Systems, and Materials. The educational background of the staff is 48% electronics, 20% physics and the remainder in other areas. In total they have about 1400 employees. This laboratory is noted for its accomplishments in low- T_c superconducting digital circuitry.

We (R.C. Dynes and R.W. Ralston) visited the Atsugi laboratories on Thursday, June 1. We left the Akasaka Tokyo Hotel at 7:30 am and took the subway (Marunouchi line) to Shinjuku Station. We boarded the Odakyu line train to Honatsugi and then a taxi to the Fujitsu Laboratories, arriving at about 9:30 am. We were greeted at the entrance to the laboratory and ushered into a conference room where we spent the remainder of the day (leaving at approximately 4:00 pm). We were not shown any individual laboratories or processing facilities and the day consisted of presentations and discussion.

We were initially greeted by Dr. Kurokawa, the managing director of the laboratory, who gave us an overview of the general philosophy of the Fujitsu research laboratories. In this overview he discussed superconductivity specifically and said that he was not optimistic about the future of Nb-based superconductor electronics, in spite of the substantial success Fujitsu enjoys in this field. He told us that there were about 20 researchers in the area of superconductivity at Fujitsu and that he saw no likelihood of this increasing unless a major advance

in superconducting materials resulted. He was rather discouraging and with many of his people in the room during this discussion we noted a rather somber tone.

Following this overview the technical presentations were quite upbeat and impressive. Dr. Nakajima followed with a more technical overview describing the size of the laboratories (1400 people) and the distribution of the programs in electronics, opto-electronics and systems. Nakajima is a research fellow at Fujitsu and had a good overview of the organization and technology.

Imamura next gave a Josephson devices overview. The program started in 1975 on Pb-based alloys and changed to Nb technology in 1983. After high- T_c superconductors were discovered half of the 6 people went into high- T_c research. Altogether there are four groups at Fujitsu working on high- T_c superconductors; these groups are:

1. High- T_c films
2. Devices
3. Superconducting materials (ceramics)
4. Superconducting materials

The ambiguity between groups 3 and 4 reflects some competition between different organizations internal to the laboratory.

The accomplishments at Fujitsu have been most impressive in the past few years, going from the demonstration of a Nb- Al_2O_3 -Nb Josephson junction in 1984 to a 10K gate array in 1988 and finally a 4 bit slice microprocessor working at 770 MHz and minimal power dissipation (0.005W). The central spark-plug in all of this effort was a young man by the name of Kotami. He clearly was the person who was the focus of these efforts and his grasp of all of the elements of this program was impressive.

We were also exposed to other programs which were aimed at superconducting electronics. Thin film growth, novel field effect devices, superconductor-semiconductor interfaces processing techniques and device applications all pointed in the direction that this was one of the serious laboratories working in the area of superconducting digital electronics. In spite of the somewhat gloomy introduction by the laboratory director, we sensed an enthusiastic and very talented staff. They showed no signs of slowing down.

B.3.2 Furukawa Research Laboratories

J. K. Hulm

The visit to Furukawa Research Laboratories, Yokohama was made by John K. Hulm.

Dr. Minoru Suzuki met me at the Akasaka Tokyu hotel and we went to the laboratories by taxi and train. I met Mr. Shoji Shiga, General Manager of the Superconducting Research and Development Department, Dr. Yasuzo Tanaka, Chief Research Engineer, Superconducting R&D Department, and Mr. Koki Tsunoda, a member of the superconductivity products department, New Business Development Division.

The Furukawa central research laboratories is in an almost brand new building about a mile from Yokohama station. I arrived there at about 11 a.m. and left at about 12 noon as Mr. Shiga had arranged a luncheon at a hotel near the railroad station. I had to return to Tokyo after lunch in order to keep appointments with officials at STA and MITI; so the actual visit to Yokohama research laboratory was quite brief.

Mr. Tsunoda described the most recent products in their line of superconducting wires and cables. These included a high current capacity Nb_3Sn conductor supplied to Lawrence Livermore Laboratory for Fusion coils, an a.c. cable for 60 Hz application with 0.5 micron strands and an advanced high current density cable supplied to the SSC. A full range of more typical Nb_3Sn and Nb-Ti conductors was also available.

Furukawa has supplied a number of magnet coils as well as cables. These include the Topaz aluminum stabilized detector coil for the Tristan accelerator, and insert coils for high field magnets at NRIM, such as Nb_3Sn and V_3Ga tape magnets. They have built a 4 tesla, 1.4 meter long dipole for a 8 GeV pion line on the 12 GeV proton synchrotron at KEK, also a 2 tesla septum magnet for the same accelerator.

It was mentioned that Furukawa had a joint venture with Oxford to build MRI magnets in Japan. Apparently the main market share in this technology is held by the three major electrical companies.

Mr. Shiga gave me a short tour of the superconductivity laboratories before lunch. Most of the work at the Central Research Laboratory is focused on the production of both thin and thick films and silver-coated wire of various high- T_c oxides. The laboratories seemed well-equipped with a variety of equipment for producing thin films, ceramic samples and experimental wires.

There was no time for an extended presentation, but Mr. Shiga gave me a set of notes on the general directions of their work. They are investigating the various well-established problems of attaining high J_c in the oxides, including weak links between grains, orientation of grains, thin films and melted

materials.

They have made thin films by Physical Vapor Deposition, using multi-source co-evaporation. By using O_2 or O_3 activation they have produced excellent high- T_c films which do not require post-annealing and have T_c equal to 85K in O_3 . The current density in the film was about 8×10^5 A/cm² but falls off rapidly with a field parallel to the c axis.

They have deposited Y-Ba-Cu-O thin films in various flexible substrates such as nickel alloys, with a copper stabilizer. J_c was $> 10^5$ A/cm² at 4.2K, but only 2.2×10^2 A/cm² at 77K, presumably in zero magnetic field.

They have prepared thick films of Y-Ba-Cu-O by various melt-texturing techniques. Single crystals give quite high current densities in the thick material.

They have made silver sheathed BSCCO wire. At 77K, J_c was about 10^4 A/cm² at 1 tesla.

They made a small coil of silver coated Y-Ba-Cu-O using 0.5 mm diameter wire. The coil was on display in the materials products exhibit room at the Central Laboratories. It generated 33 gauss in a 10 mm diameter bore with a current of 20 amperes.

They have estimated the stability diameter of Y-Ba-Cu-O wire as around 1,000 microns compared with < 100 microns for Nb-Ti.

I got the impression of a vigorous program which will probably lead to some new types of conductors in due course.

B.3.3 Hitachi (Kokubunji)

M.S. Dresselhaus

The Hitachi Central Research Laboratory at Kokubunji is located in a beautiful wooded forest, in keeping with a tradition of the Hitachi organization of locating its facilities on sites of natural beauty. This central Research Laboratory is one of 9 corporate laboratories, and was founded in 1942. The laboratory now has about 1300 employees, studying microelectronics (41%), information science (44%), and fundamental science (15%). The Central Research Laboratory at Kokubunji is organized into 10 Departments, and the Second Department, now managed by Dr. Katsuki Miyauchi, is involved with the study of Superconducting Materials and Electronics, among other topics. Almost all of the available time was spent visiting the Second Department.

With regard to company characteristics, the sales volume of the company nearly doubled in the 1979-84 time frame, but has been almost static for the past 5 years as the company changed its emphasis toward information, communication systems and electronic devices (now 44% of their business), while

decreasing their emphasis on their other businesses; transportation equipment and automotive components (10%), industrial machinery and plants (10%), consumer products (17%), and power systems and equipment (20%). The net sales of the company (not consolidated) for the past year was \$24.5 B, with a net income of \$700 M, while the R&D expenditures were \$2.2 B, giving a ratio of (R&D/sales) = 9.1%. The number of employees is currently about 78,400, with about 12,100 engaged in R&D, supported by their own laboratories at the 1/3 level and by Hitachi business groups for the remaining 2/3. The average growth in sales for the past 5 years has been approximately static (at ~ 4%/yr), while the capital expenditures last year were \$6.76 B, or 27.6% of sales.

The Hitachi corporation promotes international collaborations through support of collaborative research with foreign institutions, a foreign visitors program, support of international symposia, support of presentations of Hitachi research at satellite meetings abroad (often on foreign University campuses), and the newly formed satellite laboratory in California. For company employees, there is strong encouragement for self-study and continuing education in technical areas, to keep technical employees current in the state of the art. The philosophy of the company is emphasis on doing original, creative research with a long time horizon, as exemplified in the widely-displayed calligraphy of the founder of the Hitachi Corporation, Mr. Namihei Odaira, which they translate as "though we cannot live one hundred years, we should be concerned about one thousand years hence."

We were picked up at our hotel by Dr. Yasuo Wada, currently on leave from Hitachi to serve as technical Manager of the ERATO Quantum Flux Parametron Project (see trip report of ERATO program in Section B.1.2). We are well acquainted with Dr. Wada from the year he spent at MIT in Professor Antoniadis' group a decade ago. On the way to Kokubunji, he gave us some background information about R&D at the Central Research Laboratory, and clarified our schedule for the Hitachi visit. On arrival at the Central Research Laboratory, we were welcomed by Dr. Ushio Kawabe, chief researcher and manager of the Superconducting Electronics Research Center in the Second Department. Dr. Kawabe has an international reputation in superconducting research and kindly provided some general comments about R&D at the Hitachi Central Research Laboratory and about the Superconducting Program in particular. The Hitachi program is classified by the company as fundamental research, involves 30 people (10 in high- T_c research and 20 in low- T_c R&D) in their Kokubunji laboratory. The research program focuses on three issues: microprocessor, the superconducting transistor including wave function phenomena, and high- T_c superconducting materials research. In addition, the Central Research Laboratory is involved with the ERATO Quantum Flux Parametron Project described in section B.1.2. Dr. Kawabe's overview presen-

tations emphasized the superconducting transistor and the superconducting phototransistor as notable achievements in the area of superconductivity.

The superconducting transistor is based on the proximity effect and is the consequence of several years of basic research on the properties and functional dependence of the proximity effect in superconductor - semiconductor - superconductor junctions. The basic research program addressed such issues as the dependence of the coherence distance of the superconducting electron wavefunction on the carrier density of the semiconductor and on the spacing between the two superconducting electrodes. The effect of an applied magnetic field on the attenuation of the proximity effect, through the breaking of the Cooper pairs was also investigated. Through several detailed studies of the properties of the superconductor - semiconductor - superconductor junction and modeling of these properties for several superconductors and semiconductors, the superconducting FET was developed. This device has two superconducting electrodes on a heavily doped silicon substrate, separated by a $0.1\mu\text{m}$ gap. The superconducting current is controlled by variation of the gate bias voltage, which varies the carrier concentration in the semiconductor, and hence varies the coherence length of the superconducting wave function. The present device is based on a poly-silicon gate electrode and has a rather high resistance ($> 10\text{ k}\Omega$ at 4K), which may be high for integrated circuit applications. This device application is now being studied and further developed. During a laboratory tour, Dr. Toshikazu Nishino gave us a very clear explanation of this work, and made a very favorable impression on the quality of the people working at the Central Research Laboratory.

Another basic science project of the superconducting group concerned an early demonstration of the Bohm-Aharonov effect, which is mainly studied in the Advanced Laboratory Research Group. In this experiment, a metallic (superconducting) overlayer was deposited on a tiny toroidal ferromagnet with dimensions of $\approx 3\mu\text{m}$ and $5\mu\text{m}$ for the inner and outer diameters of the toroidal magnet. By use of electron holography, a phase shift between two electron beams (one passing through the hole of the toroid, the other outside the toroid) was demonstrated when the Nb film overlayer was in the normal state. Below the superconducting transition temperature, the electron beam could not penetrate the hole in the toroid, and an additional phase shift between the two electron beams was observed. No specific device application for this basic research was mentioned.

Characteristic of the superconducting FET and the Bohm-Aharonov studies, and their general interest in mesoscopic physics, is the use of extraordinary fabrication facilities for special small dimensional devices. This capability was discussed intensively in Dr. Kawabe's overview talk and our laboratory tour where we saw their fabrication facility for Josephson arrays through a window.

Hitachi is one of the three industrial laboratories (along with Fujitsu and NEC) with very sophisticated technology in digital superconducting electronics. The development of Josephson technology with refractory superconductors at the Electro-technical Laboratory (ETL), a MITI sponsored laboratory, is a success story of how a very sophisticated technology was developed at a national laboratory, and by involvement of industrial researchers at an early stage of the R&D program, the generic Nb/Al₂O₃/Nb Josephson junction technology was transferred effectively to three industrial companies for their potential commercialization. One of the notable achievements at the Hitachi Central Research Laboratory with this technology is a microprocessor with 2066 gates, using 5 μ m junctions and 2.5 μ m wires. Though lagging somewhat behind Fujitsu, the recent leader in the field of digital superconducting electronics, the program at Hitachi is impressive on the basis of international comparisons, and is beyond anything taking place in the United States. Dr. Kawabe has a rather positive view about the future of digital superconducting electronics, and feels that at least part of high performance future computers may have superconducting components. It is apparent that Hitachi has a long term commitment to superconducting digital electronics. Further evidence for this commitment is the Hitachi participation in the Goto ERATO-sponsored Quantum Flux Parametron project, described in the ERATO trip report (§B.1.2).

Consistent with their commitment to superconducting electronics, is their effort in high- T_c superconductivity, which is largely focused on high- T_c materials research, especially to thin film studies. It is widely appreciated that control of superconducting film technology will be vital to the application of high- T_c superconductors to electronics. One of their major interests in the high- T_c film research is the preparation of high- T_c films with high current density capabilities on semiconductors, using low processing temperatures (e.g., 600°C). To accomplish this, they showed us on the laboratory tour an electron cyclotron resonance system employing an oxygen (O₂⁺) plasma source and coevaporation of Y, Ba and Cu using an electron beam gun and a triple hearth heating system. Two separate vacuum systems were employed with differential pumping between the region where the metallic evaporation occurred and the oxygen plasma source entered. The electron cyclotron resonance system operated at 875 gauss and 2.45 GHz, and both the metal and oxygen species were incident at 45° to the substrate. Good results were obtained for YBaCuO films using temperatures as low as 510°C without additional annealing on SrTiO₃(110) substrates ($T_c = 87$ K with $J_c = 1 \times 10^5$ A/cm² at 77K) where $T_c \sim 80$ K and on Si (100) where $T_c \sim 63$ K. It appeared that work was progressing to further optimize this process.

There were also many other thin film projects. One of the more interesting ones was an attempt to prepare thin films of the electron-doped high- T_c

superconductors $(\text{Nd,Ce})_2\text{CuO}$ on an MgO (100) substrate using rf magnetron sputtering, and good success was achieved. RF magnetron sputtering was also used to prepare YBaCuO films and derivative films where other rare earths such as Er was substituted for Y. As we saw in many other laboratories, attention was being given to the control of the microstructure to enhance the critical current density. With regard to applications, the Hitachi researchers were working on SQUID devices as well as a superconducting optical detector based on $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ on a MgO substrate whereby light provided by an optical fiber was incident on a photoconductive semiconductor, the proximity effect between the superconducting electrodes could be varied. This concept seemed related to the superconducting FET which was implemented in low- T_c materials.

The particular day of our visit was the first working day for the new Director, General Manager of the Central Research Laboratory, Dr. Hiashi Horikushi, in his new position. Dr. Horikushi is a specialist in the computer area. Despite his very busy schedule for that day, which included hosting a dinner party, officiating at a laboratory-wide celebration with fireworks, and a host of other duties, he nevertheless found time to greet us and to give us an overview of R&D at Hitachi. This day was also the first day for Dr. Miyauchi as Manager of the Second Department, where Superconductivity Research was carried out. We were quite surprised by the youth of the Manager of such a large department, and were told that it is the Hitachi policy to promote their most talented and energetic people to responsible positions during the most active period of their careers.

Following a very intensive and stimulating visit, we were invited to dinner at Shikitei, and extraordinary restaurant, where we enjoyed a wonderful meal with stimulating conversation with Drs. Kawabe, Wada, Tsumita and Miyauchi. We were pleased to see Dr. Norikazu Tsumita again and to learn that he was now chief engineer at the Hitachi Odowara works, (officially called chief engineer of the Magnetic Disk Media Engineering Department). Our hosts were very interested in the impression of the American JTEC team on superconductivity research in Japan.

B.3.4 Hitachi Research Laboratory (Ibaraki)

M.S. Dresselhaus

This visit to the Hitachi Ibaraki Research Laboratory was made with Dr. John Hulm (Westinghouse - retired) and Dr. Nobuyuki Kambe (NTT). We arrived at the Hitachi Research Laboratory at 12:30 pm, on time, having just driven up a wonderful park. rising to the high elevation where the research laboratory is

located. The site is spectacular and has a commanding view of the countryside, reminding me of the lovely Hitachi research laboratory near Tsukuba where the Mechanical Engineering Department is located.

Our briefings started in the traditional small conference room. We had a briefing of the whole company by Dr. Motohisa Nishihara, Director of the Hitachi Research Laboratory and Mr. Munehiko Tonami, Manager of International Relations of the Hitachi Research Laboratory. They spoke with much enthusiasm about the Hitachi seminars held at MIT and Stanford, briefing faculty and students of their technical R&D achievements at Hitachi.

The philosophy of the company is a long term view. Last year they had \$25 B in sales, bringing them into 16th place in international rankings on business size, with 38% of the business in electronics, 38% in materials, and 24% in energy. They put 9% of their annual sales into R&D. They were very proud of their management of R&D especially two approaches that they explained to us. One is an Idea Express Program providing support for up to 6 months (at about the \$35K level in addition to salary) to try out new ideas. The money for the Idea Express R&D is provided by pocket money from each Laboratory Director, with a minimum of bureaucracy. In addition, they had a Feasibility Test Program which provided support for 6 - 24 months with no budget upper bound to do more intensive R&D on the good ideas. These are two mechanisms used by Hitachi for accelerating the development of new ideas.

We then got briefings on the superconducting technology program, which included generators, magnets, magnetic resonance imaging units, a small scale synchrotron orbital radiation (SOR) project, superconducting electronics (Josephson Junctions and superconducting transistors), and an exploratory high- T_c superconductivity program.

We then got a briefing by Dr. Shinpei Matsuda on the history of superconductivity R&D at Hitachi and their resulting Hitachi product line. The R&D program started in 1962 with research on Nb alloys and then got more serious in 1967 when they started building superconducting magnets for magnetohydrodynamics (MHD) systems. Then in 1970, they got involved with the new magnetic levitation program and started developing superconducting magnets for that type of application. Their research on superconducting generators started about 1980, and their Josephson device program in 1984. Aside from superconducting electronics which is studied in the Kokubunji laboratories, most of the superconductivity research is done at the Hitachi Ibaraki Research Laboratories, but significant activity also occurs in the Hitachi Works (as they call their manufacturing centers) and in the Hitachi Wire and Cable Company, one of their subsidiaries. The most impressive aspect of the Hitachi program is their historical record. Hitachi entered this technological field in the early 1960's, at a time when other companies like Westinghouse and GE were

already well established. Hitachi got started slowly on the technology development curve, got one contract that advanced them on the learning curve, and then they had a steady sequence of one contract after another to advance them on the learning curve, eventually putting them in a highly competitive international position by sustained support and long term follow-through. They now have about 40 people involved in superconductivity research emanating from the Ibaraki laboratory, both on-site and elsewhere. We later saw a very similar pattern at their competitor companies, Mitsubishi Electric and Toshiba.

Hitachi's sustained superconductivity work is largely focused on low T_c superconductors and involves real products, magnets for vehicles, magnets for accelerators, magnets for MRI machines and associated systems. The production is continuous, so there is activity ranging from exploratory R&D to development work, and a very small amount of basic research. They took us for an excellent tour of their R&D laboratories and facilities. The Hitachi researchers were fully open to us and were perfect hosts in every way. We saw a number of excellent programs, as we toured the laboratories, but perhaps the most impressive was the very large scale of their R&D program involving many large laboratories with very large amounts of sophisticated engineering equipment. One large room was devoted to R&D on rotating machinery, another large laboratory was developing a 20T superconducting magnet based on 2 inserts into a main-frame magnet, each insert operated separately and based on different superconducting materials. The engineering was very sophisticated and methodical. The order and cleanliness of the laboratories was impressive.

Another project they were excited about was the R&D for the superconducting magnets for the synchrotron orbital radiation machine (SOR), what we call a table-top synchrotron machine, to be used for submicron lithography applications for the semiconductor industry. In getting into these new areas, the Hitachi managers do not aim on making money right away, but rather on developing their technology. The Japanese seem convinced that the semiconductor manufacturers will require table-top SOR machines and are investing large amounts of money in developing these machines. The SOR machine that was built for NIT had a price tag of \$200 M. At that price, Americans are asking whether there may be a better technology.

After this part of the laboratory tours, we went to another location where they had their high T_c superconductivity program. As a demonstration they showed the usual levitated high- T_c disk, but this time orbiting a track provided by electromagnets and coils that were phased around the track. This was a nice demonstration of their Maglev (magnetically levitated train) concept.

Their "basic" high T_c research program was mostly on new compounds and on their characterization. This was good systematic materials research, highly appropriate for research in an industrial company. They presented some struc-

tural thin film studies on the BiSrCaCuO system directed toward enhancing the $T_c = 110\text{K}$ phase. They had significantly more emphasis on their wire program than on their thin films. For example, they were making superconducting tapes using a silver tube for packing the high- T_c powders and then drawing down the tubes to thin filaments ($\sim 5\mu\text{m}$). They reported tapes based on TlBaCaCuO with $T_c = 120\text{K}$ and $J_c \approx 10^4 \text{ A/cm}^2$, which once held the world record, but was soon broken by achievements at other laboratories. They concluded that the cold rolling process helped to produce preferred orientation of the grains with their c -axes along the tape direction. They were doing good work on the superconducting tapes and were optimistic about their approach for enhancing J_c . As Dr. Matsuda said to us, if you are leading a group of researchers, you had better feel optimistic.

B.3.5 Matsushita

M.S. Dresselhaus

Dr. Tsuneharu Nitta, Director of the Central Research Laboratory received us on arrival at the Matsushita International R&D Center and provided us with an overview of the company and of the research laboratory. Although Dr. Nitta was very conversant in English, he preferred to speak to us (M.B. Maple, J.K. Hulm, R. Quinn, P.M. Horn, Mildred Dresselhaus and Paul Herer) through a translator, Mr. Shigeyoshi Moriyama, General Manager of the Technical Liaison of the International R&D Center, who designated himself as the JTEC contact person at Matsushita.

Matsushita is the largest Japanese company in the electrical products business with annual sales in the \$38 B range, and a growth rate of 7.6%/year. While Matsushita already has the largest market share of home appliances in Japan, the company is now putting more emphasis on factory automation, computers and communication. In the home appliance area, they are promoting sale of kitchen systems, where each system could run in the range of \$20K to \$40K per system. Whereas their overall R&D is at the level of 6% of sales, their semiconductor and computer divisions has a significantly higher R&D level ($\approx 10\%$ of sales).

Although the Matsushita management had no plans to use the high- T_c oxide superconductors in a product in the foreseeable future, the company has a long-term commitment to increase the level of understanding of the oxide superconductors. Following his presentation to us, Dr. Nitta left for a business meeting in Tokyo. As Dr. Nitta left the room, several of the key researchers and managers entered, all attired in similar blue company outfits, as is common in Japanese industrial laboratories to show that workers at every level are

important members of the corporate team and all must contribute at their maximum level of commitment to the benefit of the company.

Following the presentation of Dr. Nitta, we had some general discussions about the Matsushita program on superconductivity by Dr. Wasa. Before the advent of high- T_c superconductivity only one or two of the entire staff at the Matsushita Central Research Laboratory were working on superconductivity. Their present significant activity in superconductivity therefore represents a reassignment of about 30 researchers to superconductivity projects, about half of these being Ph.D.s. The overall R&D program at Matsushita is very broad, supporting a huge range of products in consumer electronics, office automation, audio-visual equipment, robots for industrial applications, home appliances, communications equipment, batteries, electronic components, etc. There are about 300 researchers in their Central Research Laboratory, working on a broad spectrum of research projects. The researchers are divided into a Materials Research Division, which is mainly involved with Ceramics and a Materials Science Research Laboratory that is mainly concerned with thin films and devices. In addition, the Matsushita Technical Research Center provides valuable support in the characterization of materials. The early work in the Central Research Laboratory dates back to 1960, when Matsushita started a research program on ceramics, mainly of the perovskite structure, and in this period some of the pioneering research on the sputter deposition of thin ceramic films was carried out by Dr. Nitta and his group. Dr. Wasa was a pioneer in the development of the magnetic sputtering technique. An important achievement of the laboratory was the first synthesis of single crystal thin films of Pb-La-Ti-O which they called PLT films. In 1980 they started work on artificial metallic, superconducting and ceramic superlattices, exploiting their experience with sputtering and thin film technology. Thus, it is easy to see why the researchers at Matsushita were well positioned to respond to the announcement of the discovery of ceramic high- T_c superconductivity.

When asked about their ideas for product applications of the high T_c materials, the Matsushita leaders did not have too many clear plans. Some of their thoughts included high speed input devices for information systems, high density memories based on magnetic flux quanta, and interconnects to silicon. The Matsushita leadership was targeting their program to 77K applications for the next decade and perhaps room temperature applications at a future time. The Matsushita researchers did not feel that the oxide superconductors would be useful for large motor applications, largely because of reliability considerations.

Mr. Shun-ichiro Kawashima, Senior Researcher in the Materials and Applications Group, of the Central Research Laboratory, provided an overview of their high- T_c materials program which was directed towards the search for new superconductors and their characterization, the identification of the crystal

structure of the compounds (they were one of the early groups to identify the crystal structure of some of the Bi-Ln-Ca-Cu-O phases), efforts to increase the number of CuO_2 layers per unit cell, study of the relation between fabrication conditions and superconducting properties, and isolation and properties study of the "2223" Tl compounds with $T_c \approx 120\text{K}$. In their quest for new superconducting materials they told us that they had independently discovered 4 new oxide superconducting compounds at Matsushita and had characterized them. Mr. Kawashima then went on to describe the relations between the Matsushita Company and ISTECC. Thus far Matsushita had sent one of their researchers to ISTECC, and had only weak ties to this employee who was based in Tokyo and was working on fundamental research on the high- T_c oxide superconductors, unrelated to anything he had done previously at Matsushita, nor related to anything of direct interest to the company. In terms of interaction, this employee was obliged to send one short report per month to his supervisor at Matsushita. The company's expectations were to contribute to the enhancement of world knowledge, to enhance the background of the visiting researcher who would then transfer this knowhow in some general way to the company. They did not have any expectations for any short term benefit to the company, despite the large amount of money they were contributing to ISTECC.

Following the general talks by Dr. Nitta and Dr. Wasa, several researchers presented more detailed presentations of their on-going work. Mr. Hideaki Adachi, a researcher from the Materials Science Laboratory described his 4 target layer by layer sputter deposition system for preparation of Bi compounds with the "2212", "2223" and "2234" phases. His objective was to increase the number of CuO_2 layers in a controlled way and he was having some success with his system. Similar work was also going on for the Tl system, where they reported success with the growth of 5 CuO_2 layers. This was an impressive achievement. In addition, Mr. Adachi was preparing Nd-Ce-Cu-O thin film electron-doped oxide superconductors with a $T_c \sim 17\text{K}$.

The next speaker, Dr. Shin-ichiro Hatta, a Senior Researcher at the Materials Science Laboratory, spoke about his work on flux creep behavior in the Tl-Ba-Ca-Cu-O system and showed some interesting results on time dependent magnetization effects.

The next speaker was Mr. Hidetaka Higashima, another researcher from the Materials Science Laboratory, who spoke to us about his work on three terminal high- T_c superconducting devices with dual gate electrodes. His work was based on BSCCO, and since his T_c was only 69K, his devices could not be operated at 77K, a temperature of obvious interest for commercial applications. He also told us that he had not been successful in preparing any good tunnel junctions.

The last talk was again given by Dr. Kiyotaka Wasa, general Manager of

the Materials Science Laboratory, who had spoken to us before. Dr. Wasa is a good friend of my colleague Dr. Ko Sugihara, who had spent his entire research career at the Matsushita Central Research Laboratory, before coming to MIT after his retirement. Dr. Wasa started his talk with friendly greetings to and from Dr. Sugihara. Dr. Wasa's presentation was on the low temperature growth and deposition of high- T_c materials on Si using various barrier materials at the interface. He reported that the Matsushita researchers had succeeded in producing a c -axis oriented film using a Pt layer at the interface. The work on this project was mainly being done by a visiting lady scientist from the University of South Carolina, whom Professor Maple knew. I had also previously heard about her through Professor Datta, a Professor in the Physics Department at South Carolina, and the author of a book on high- T_c superconductivity. In his presentation, Dr. Wasa emphasized the materials science problems of lattice mismatch and interdiffusion which complicated the deposition of ordered films on the Si substrates.

The superconductivity program at Matsushita was quite new, and was making good progress. Because of their leadership position in consumer electronics, the Matsushita management felt that the company must be involved in high- T_c superconductivity research, although they had essentially no prior experience in superconductivity.

B.3.6 Mitsubishi Electric Corporation

M.S. Dresselhaus

Our JTEC group, consisting of John Hulm, Brian Maple, Paul Horn, Paul Herer and Mildred Dresselhaus, arrived at the Mitsubishi Central Research Laboratory about 12:30p.m., a half hour before our scheduled arrival. Thus we had lunch with Dr. Masatami Iwamoto upon arrival.

As a result of the lunch, we arrived back to the central research laboratory approximately half an hour behind schedule. We then proceeded with their scheduled activities. First we saw a movie on the Mitsubishi electric businesses, including space development, Communications and Information Processing Systems, Electronic Devices, Energy, Transportation, Large scale Building Equipment and Systems, Industrial Equipment, Audio-visual Equipment and Home Electronics. Because of their heavy involvement with superconductivity equipment and materials, Mitsubishi electric was one of the companies of particular interest to us.

After the film was completed, our hosts asked for information from us. I explained the ground rules of our JTEC study, which was followed by an overview of the IBM R&D program on superconductivity, and their particular interest in

possible superconducting electronics applications. Our hosts then asked about the IBM-AT&T Bell-Lincoln Lab-MIT Superconductivity Consortium, which Paul Horn explained, and of course there was great interest in the consortium on the part of the Mitsubishi people.

Following Paul Horn, Rod Quinn gave an overview of superconductivity research at Los Alamos, followed by John Hulm, who made some comments on the Westinghouse program. The number of researchers in superconductivity on the U.S. side was given as 65 at IBM, 30 at Westinghouse, and 60 at Los Alamos. We heard that 3 Mitsubishi Electric researchers were sent on assignment to ISTEK and we also heard that two members of the Kobe works joined a study for the SSC magnet design. Of the researchers sent to ISTEK, two were from the Central Research Laboratories and one was from the Materials Research Laboratory

Dr. Iwamoto then gave us an overview of the Mitsubishi Electric Program on Superconductivity which was very extensive. At the Central Research Laboratories they were concerned with Applications, Cryogenics, and SQUIDS. Their cryogenic program started in 1958, 37 years after the start of the company in 1921, leading to the first successful liquefaction of helium in Japan in the early 1960s. Since that time Mitsubishi has been heavily involved in developing refrigeration systems for research projects for the Electrotechnical Laboratory (ETL), for the Japanese Atomic Energy Research Institute (JAERI), as well as commercial refrigerators and liquefiers. Liquid helium refrigeration systems could be an important business for supplying helium for superconducting accelerator magnets, magnetic levitation applications and superconducting generator sets. Their Josephson effect program started in 1970 and under MITI sponsorship Josephson integrated circuits and mixers were developed.

Research on conventional superconducting materials for wire applications has been active and sustained since 1961 with particularly good work done on the development of fine filamentary wires, the R&D on Nb_3Sn wire for magnet applications and building practical magnets on these wires, enhancing the state of the art with the Nb-Ti materials by alloy additions and processing. Their work on superconducting magnets dates back to 1961. They were fortunate in having had a series of contracts to build various superconducting magnets dating back to about 1964, which allowed them to get on top of the state of the art in this field. The projects included building a Nb-Ti-Ta solenoid for ETL, a Nb_3Sn quadrupole magnet for KEK (The Japanese National High Energy Physics Lab), a magnet for plasma fusion applications, a large cable coil for MITI, a pulsed magnet with 200T/sec capability for the Institute for Plasma Fusion, a forced cooling coil for JAERI, among others. This steady construction business has significantly added to their technical know-how, and put them in an excellent position to supply MRI magnet systems when that

market opened up. In parallel with the magnet construction is a history in magnetic levitation R&D going back to 1969 and continuing into the future, involving the construction of both the magnetically levitated vehicles, but also the refrigerator systems. Of course now they are looking into the possibility of using high- T_c materials for magnetic levitated train applications. Although the application may be years in the future, they do not want to be left out of the race in this technology. In presenting the actual overview, Dr. Iwamoto carefully laid the historic achievements in perspective.

The presentation by Dr. Iwamoto was followed by a presentation by Dr. Takashi Noguchi of the Central Research Laboratory who described their SQUID device work which until now was with conventional superconductors, and was aimed at giving lower performance by reducing junction inductance and capacitance. He showed that the SQUIDS could give magneto-cardiogram signals as good as the electrocardiograms we are accustomed to. We were told that the researchers at Mitsubishi are now trying to make SQUIDS with high- T_c materials. Dr. Noguchi then described their thin film program which was quite extensive, with 10-15 people engaged in this program. They were making both the Y-Ba-Cu-O and Bi families of thin films by a variety of techniques including sputtering, reactive evaporation, MOCVD, laser PVD among others and they were getting respectable J_c values (5×10^5 A/cm² for Y-Ba-Cu-O at 77K) and were having some success in a magnetic field up to 1T, but large dips in J_c above that level. Their goals for the SQUID were for ferromagnetic applications, low noise RF amplifier, mixers and magnetic scanning.

We then heard from Dr. Ken Sato, manager of the Metals and Ceramics Department. He first described the doping experiments to enhance the field range achievable with the Nb₃Sn magnets. He described one where T_c additions were used to achieve a 12-16T superconducting magnet. also under development is a hybrid magnet operating in the 18-20T range but using a wire based on a chevrel phase material (PbMo₆S₈) prepared in wire form by a powder process. This work on magnet wires based on chevrel phase materials was pioneering and could lead to some technological advance.

With regard to the high- T_c materials, there was ongoing work on thin films, thick films, bulk materials and characterization and evaluation. They were using an ionized cluster beam method invented at Kyoto University with some success and they were using MgO and MgTiO₃ substrates.

For their thick films, they were using a sol-gel process and were having difficulty with removing all of their carbon in the processing. For the wire conductors, they were using a five particle deposition and sol-gel method. Their emphasis was on fundamental problems of grain growth and flux motion. They had not made coils. They said that they would soon be making multifilamentary high- T_c wires.

B.3.7 NEC

M.S. Dresselhaus

This visit to NEC was carried out together with Dr. William Gallagher of IBM. We were met at the Miyazakidai station by Mr. Koichi Yoshimi, who then took us by taxi to the nearby NEC Central Research Laboratory with the usual Japanese efficiency. There, we were greeted by our chief host Dr. Michiyuki Uenohara, Director of Research of the NEC Central Laboratory, who briefly explained the goals of the company in home electronics, electronic devices, computers and communications. The history of the company in communications, dating back to 1899, was reviewed, as was the recent growth into the new areas mentioned above. The annual sales of the company are now \$22 B, with 100,000 employees, having 70% of their business within Japan, and 30% abroad. Their research laboratories have about 1000 employees, with about 1% of the total NEC annual sales going into R&D aimed at long term research (the day after tomorrow) and 9% going into shorter term horizons (tomorrow and today). Although we saw some examples of basic research, the focus was very much on R&D with perceived relevance to potential products. After his presentation, Dr. Uenohara had to leave because of his commitment to the orientation of a new crop of engineers who had just joined the company. As is their custom, Japanese companies take this company orientation and education program very seriously, and top people in the corporation are involved in the process.

Following these more general discussions, our other host Dr. Fujio Saito gave us a presentation on the NEC overall Superconductivity Program which included three major topical areas: materials science and physics; thin film processing and finally applications. Within the realm of materials science and physics, many subtopics were listed: synthesis and structure, transport and magnetic properties, tunneling in high- T_c materials, band calculations of high- T_c materials, the relation between oxygen stoichiometry and materials properties, rare earth substitution studies, collaborative studies on magnetic structure, energy gap anisotropy studies by tunneling, among others. For the thin film processing, several topics were listed, including a range of processing technologies they were working on, such as plasma-assisted vapor deposition, RF magnetism sputtering, ion beam sputtering, electron beam vapor deposition, and chemical vapor deposition. They were giving significant emphasis to thin film growth and characterization, with potential device applications as their R&D impetus. Particular attention was given to epitaxial growth of high- T_c materials on Si wafers, and they were very proud of their outstanding achievements in this area. Their applications work was significantly focused on microfabrication and patterning, with major efforts in reactive ion etching,

ion implantation, and fine line fabrication. They noted their extensive past experience in ceramics technology and the importance of this background to their advances in processing technologies and microfabrication.

This overview was followed by a request for me to explain in some detail what was the objective of the JTEC Study on High- T_c Superconductivity and for Bill Gallagher to give an overview of current superconductivity research at IBM, including advances not yet published. They reciprocated with an overview of more in-depth discussion of 8 topics, almost all on work already published. We were not invited into their

Dr. Sumio Iijima, senior research manager of their Exploratory Research Laboratory, gave an interesting presentation showing some wonderful electron microscopy results for electron beam induced preferential atomic motion of species in the amorphous phase relative to the crystalline phase. The results were shown for high- T_c superconducting materials as well as for other materials. Dr. Iijima also spoke about crystal structure determinations of high- T_c materials. Their efforts to correlate microstructure and superconducting performance were of limited success.

Mr. Yoshimi Kubo then described their studies relating oxygen uptake to T_c , the superconducting transition temperature, for various Bi compounds including "2201", "2212", and "2223" phases. As also shown by many others, relatively small changes in oxygen concentration had large changes in T_c , and the effect was much larger for some high- T_c phases than others. A good correlation between c-axis lattice constant and T_c was shown.

Dr. Jaw-Shen Tsai, one of their best known researchers, gave an interesting presentation on his studies of the anisotropy of the superconducting energy gap based on tunneling spectroscopy studies. He introduced a clever method for cleaving high- T_c materials and introducing a Pb layer near the high T_c film surface for making tunneling measurements on the Bi high T_c materials. Systematic differences were seen for tunneling into (001) and (110) faces, and these differences were attributed to an anisotropic energy gap. The results were promising in terms of the temperature dependence of the energy gap, but the error bars were too large to yield a definitive functional form for the temperature dependence of the superconducting energy gap $\Delta(T)$. Dr. Tsai was also very active with Josephson junction applications, but did not talk about this work.

Mr. Hisanao Tsuge, manager of their Advanced Device Research Laboratory gave a very nice presentation summarizing their microfabrication techniques using ion beam etching, focused ion beams, reactive ion etching and patterning by ion beam implantation. Many of their processing steps stem from their experience with ceramics and ferrites. He showed a $0.8\mu\text{m}$ stripe that was a millimeter in length with excellent uniformity. Careful evaluation

of performance (T_c and J_c) was made as a function of the width of the stripes; no change in T_c was observed for widths above $1.3\mu\text{m}$ and no change in J_c for widths above $2.3\mu\text{m}$. They attributed degradation of superconducting properties in the thinner stripes to inhomogeneities in thin film materials and not to damage due to their processing steps.

Mr. Tsuge then showed examples of their processing technology applied to low- T_c Josephson junctions. They were especially proud of their non-destructive readout capabilities in Josephson junction 1 kbit RAM devices, which they felt were at the state of the art. They provided some comparisons between the performance of their memory chips with those of Fujitsu and the Electrotechnical Laboratory (ETL) in Tsukuba.

A review of the NEC work on Bi thin film high- T_c was presented by Mr. Tsutomu Yoshitake, including coevaporation, ion beam sputtering and RF sputtering, which they found to yield the best films. Their work was very systematic and was significantly directed toward establishing the conditions for enhancing the 110K phase in relation to the 90K phase, and they showed significant success. Though their work was very good, comparable efforts exist in other laboratories in Japan and elsewhere.

Mr. Y. Miyasaka gave a very interesting presentation on their work with epitaxial growth of high- T_c films on Si. This work was exceptional and should be so cited in the report. By preparing a buffer layer of MgAl_2O_4 (spinel structure) on (100) Si they are able to get good epitaxial growth ($a = 8.06\text{\AA}$ for the spinel which is approximately $(\frac{3}{2})$ the lattice constant of 5.43\AA for Si). On top of the spinel they deposit a thin layer of BiTiO_3 or SiTiO_3 by RF magnetron sputtering, forming the substrate for the "123" high- T_c materials. The best samples were made through a collaboration with Dr. T. Venkatesan of Bellcore, who prepared laser sputtered "123" films on these NEC substrates (1000\AA Y-Ba-Cu-O, 3500\AA BaTiO_3 , 750\AA MgAl_2O_4) achieving $T_c = 86\text{K}$ with very sharp superconducting onset, and excellent J_c values both at low T and at 77K .

Dr. Shinji Matsui of the Exploratory Research Laboratory gave the last presentation on microfabrication technology to produce patterning on the high- T_c materials. Reactive ion beam etching techniques for YBaCuO were described and the use of various photoresists, taken over from silicon technology. He showed examples of $0.5\mu\text{m}$ diameter wires, 1 mm in length. Ion beams were used for patterning, often with complicated irradiation schedules to get quite uniform ion beam profiles. They showed examples of selective doping and the control of local materials modification through ion implantation. Their etching rate for the high- T_c materials was close to that for silicon.

In general the Japanese industrial companies have strong collaborative programs within a company, but almost no interaction with researchers at other

companies, or national laboratories or universities. The materials work at each company seemed to be directed toward independent technology development for that company. However, collaborations with researchers in the U.S., whether in industry or universities seemed possible, if there was mutual enhancement of their technologies. Thus the high level of laser beam sputtering technology offered by Venkatesan of Bellcore made a collaboration with NEC researchers possible, with NEC supplying the best silicon substrates available anywhere. Since NEC had little prior experience in conventional superconductivity, their activities were strongly directed toward the high- T_c oxide superconductors.

B.3.8 NTT (Ibaraki)

R.C. Dynes

We (R.C. Dynes, W.J. Gallagher, R.W. Ralston) visited the NTT Ibaraki Laboratories on Friday, June 2 on our way to Sendai. There are two NTT electronics research laboratories, one at Ibaraki and one at Musashino. The Musashino laboratory is the more basic of the research laboratories and the research at Ibaraki is aimed at opto-electronics. Our host for the visit was A. Yamaji who met us at the Katsuta train station at approximately 11:00 am. We were taken to the Ibaraki laboratory where we were given a brief overview of the NTT laboratories and then more specifically the NTT Ibaraki laboratory. A rather extensive ($\sim 1\frac{1}{2}$ hr) lunch followed this introduction where we were treated to a magnificent view along the coastline. The afternoon was then spent in technical presentations and laboratory visits.

It was clear from these presentations that NTT has a strong tradition and commitment to quality materials. The basic studies were very heavily dependent on synthesis of materials both in thin film form and single crystal. The investment of resources for both fabrication and characterization was clear and growing. We were shown a thin film synthesis laboratory which had at least 8 sputtering chambers and an MBE apparatus. We were told that a new MBE apparatus was on order and a substantial amount of clean-room space for sample processing was being built. The characterization laboratory had an impressive array of equipment, all ready for use. The interesting aspect of this was that there was apparently much more equipment than people around the equipment, unlike the laboratories in the U.S. where people are now likely to be "lined up" waiting to use equipment.

The technical presentations were quite impressive. M. Suzuki showed us his work on studying the systematics of the optical properties of thin films of $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$ as a function of x . Tajima showed us his pressure dependence of T_c on BiSrCaCuO , LaSrCuO_4 and YBCO. By far the most impressive sight

was the single crystals grown by Hidaka. This person has put NTT on the research map on the basis of his single crystals and he is clearly very talented. While there, he showed us a single crystal of $\text{Nd}_{2-x}\text{Ce}_x\text{CuO}_{4-y}$ which was ≈ 5 cm across! This particular crystal was in the insulating state and it was stated that as the materials became metallic, the crystal size decreased. Nevertheless, these crystals are the most impressive we have seen anywhere.

In summary, we were impressed with the commitment to basic research at NTT. They clearly believe that basic research results in understanding that in the long term results in applications but they have a very long term view of the applications process. There was realistic enthusiasm for the future of high- T_c superconductivity.

B.3.9 NTT (Musashino)

R.C. Dynes

On Tuesday, June 6, I visited NTT Basic Research Laboratories in Musashino. My host was Y. Kato, who is the Associate Vice President responsible for basic research at NTT. I have known Dr. Kato for some time through AT&T—NTT exchanges and the visit was especially cordial. I was met at the Akasaka Tokyu Hotel by N. Kambe who was very much our translator for the entire visit to Japan but is also on the scientific staff at the NTT basic research laboratories.

I was first given an overview of NTT basic research by Dr. Kato. In the discussion that followed, it was clear that a lasting commitment to research exists at NTT over the entire spectrum, from the most basic to the very applied. NTT has in their more applied areas built a superconducting synchrotron for studies of x-ray lithography. This machine had just been turned on 1.5 months earlier and was functioning and everyone was still quite proud of that accomplishment.

At my request I was shown a laboratory where some very bright and enthusiastic people were studying the interaction of stimuli and brain waves using a commercial superconducting magnetometer array. This instrumentation was from a U.S. manufacturer and they had a most impressive installation. They were in the process of accumulating data mapping visual and audio stimuli with brain-wave patterns.

I then was presented with an all-too brief description of the superconducting research at the laboratories. As in almost all of the visits, this work heavily relied on high quality materials. Although I didn't have much time to discuss this work (synthesis, transport, optical properties in thin films), it is my impression that it is of the highest quality.

I had lunch with Drs. Kato and Kambe and we had a most interesting conversation about the collaborations (or lack of collaborations) with universities.

Because Dr. Kato and I know each other, we discussed rather openly the differences between my institution (AT&T Bell Laboratories) and his (NTT). Much of my opinion on the interactions between industry and academia was formed or confirmed in this conversation.

In summary, NTT is a corporation which has had a long history of commitment to basic research and that continues. Their investment in high- T_c superconductivity clearly reflects this opinion, although they (as have most Japanese researchers whom we visited) have been sobered somewhat from the early euphoric days. Nevertheless, they believe that high- T_c superconductivity will significantly impact future technology and are committing resources to that end.

B.3.10 Sumitomo Electric

M.S. Dresselhaus

As we disembarked from the Shinkansen, we were immediately received at the track (car 8) by Mr. Miyazaki, who is a researcher at Sumitomo Electric, and an assistant to Dr. Tsueno Nakahara, director of research at Sumitomo Electric. Dr. Nakahara is very well known in the United States, and was known to many members of the JTEC team. Sumitomo Electric had a company bus waiting for us at the train station and we were directly taken from the train station to the research laboratory, arriving at the appointed time of 1:30 pm. Because Dr. Nakahara was in the United States, we were received by Mr. Hajime Hitotsuyanagi, Deputy General Manager of the Osaka Research Laboratories, Mr. Maumi Kawashima, Deputy Senior Manager of the R&D Group, Dr. Koji Tada, General Manager of the Basic High Technology Laboratories R&D Group, and Mr. Ken Sato, Chief Research Associate of the Osaka Research Laboratory.

Mr. Hitotsuyanagi and Mr. Kawashima provided the opening remarks, greetings and introductions. We were then taken to a nearby location where we saw an excellent movie on Sumitomo Electric that gave us insight into the overall operations of Sumitomo. This was followed by a very brief tour of their showroom. This part of our visit was kept to a minimum because they knew that we wanted to have a technical information exchange and a tour of their actual R&D facility which they did provide for us very openly.

The first technical presentation was by Mr. Ken Sato and was on conventional superconducting materials, starting with Nb/Ti and Al stabilized Nb/Ti. He reviewed many of their achievements in advanced superconducting wire materials and magnet design through illustrations of a number of magnet systems they had built. They were building high field magnets with very large bores for the growth of state-of-the-art GaAs single crystal boules to damp eddy currents

and convection flow, MRI magnets where they were competing with Furukawa, Hitachi, and Toshiba, pulsed magnets with very high ramp rates (6 tesla/sec) for use in fusion applications at the Japan Atomic Energy Research Institute (JAERI), research magnets for stator applications carried out in collaboration with ETL where researchers at Sumitomo Electric believe that they can reach the 50 kW/m^3 goal of MITI for this application. Sumitomo Electric was working closely with ETL in developing a high field magnet for ETL with 20 double pancakes for energy storage applications. Sumitomo Electric was also developing magnets for electrical propulsion of ships using an MHD method. They were also developing a synchrotron orbital radiation system in collaboration with ETL for lithography applications. Sumitomo is perhaps only working on the wire development part of the superconducting magnet. Sumitomo Electric is one of the world leaders in superconducting materials, and they are putting much effort into staying on top. They do this by their involvement in R&D activities which enhance their long-term state of the art, and the R&D is paid for mainly by the large national laboratory projects. They have about 15 people working on their conventional superconductivity program.

The next talk was by Mr. Kenjiro Higaki, a researcher in R&D who described the Sumitomo Electric thin film high- T_c program. Higaki's group were working on all high- T_c systems of interest: the "123", Bi, and Tl compounds and they were systematically investigating the relation between the superconducting properties and the substrate temperatures, annealing temperatures and many other parameters in order to optimize J_c . The best results were obtained for $\vec{I} \parallel \vec{H}$ because of the absence of a Lorentz force in this case, though there was some controversy regarding the detailed results at the various laboratories. The Sumitomo researchers were achieving among the best results in the world on J_c values at 77K and in the presence of a magnetic field. The rewards from the pursuit of systematic optimization of parameters were now beginning to be reaped. The Sumitomo Electric program also benefited from state of the art equipment and good collaboration between various divisions.

The next presentation was again by Mr. Ken Sato who described their high- T_c wire processing research program. This was truly impressive state of the art material science work. Working with a silver tube processing method, these researchers were achieving $J_c \sim 1.7 \times 10^4 \text{ A/cm}^2$, better than NRIM results by an order of magnitude. They also announced to us their goal of achieving 10^5 A/cm^2 by the end of the calendar year. Mr. Sato then showed us beautiful HRTEM lattice fringes showing small particle precipitates at the grain boundaries, and excellent contrast of the lattice fringes for the superconducting domains and for the non-superconducting domains. With the YBaCuO system they were starting to prepare small test magnets (64 Gauss), which would then be scaled up periodically to advance on the learning curve. This was a most

impressive performance.

The next speaker was Dr. Koji Tada, general manager of the basic high technology R&D group. His research thrust was along three directions, the first being the modifications of presently known high- T_c materials to enhance their performance. Dr. Tada showed us a number of examples of systematic studies synthesis studies leading to the preparation of 6 CuO_2 layers per unit cell, and systematic doping studies. Their systematic studies of the phase diagram of these compounds represented a very large amount of work, but the rewards were significant in learning how to prepare those single phase materials with the most desirable superconducting properties. The third research area was in organic superconductors where we got a lot of the same lecture we had heard before, starting at the ISSP. The researchers at Sumitomo Electric were obtaining $T_c = 11.1\text{K}$ value for their best BEDT-TTF materials, which is about the highest T_c obtained thus far with an organic superconductor. Dr. Tada told us that he had 1.5 people engaged in research on organic superconductors and 3.5 people working on other basic high- T_c materials studies, with about 3 more people collaborating on properties measurements. Of these 8 people, 3 had doctors degrees. All members of the JTEC team were highly impressed by Dr. Tada's overall presentation.

Following these Sumitomo Electric presentations, Dr. Paul Horn of IBM made a presentation from the American side, telling about the high- T_c superconductivity program at IBM, and showing some comparative tables of thin film growth in the U.S. and worldwide. We then presented them with a book on superconductivity research funding in the U.S., which interested them.

After a rather intense discussion which they enjoyed very much, as we did also, we had a laboratory tour where they were making thin films, and we also saw their x-ray characterization laboratory. These clean laboratories were kept very neat and clean, the equipment was very fancy and they had a lot of state of the art equipment, sputtering systems, ion beam deposition systems, mostly Japanese-made.

On the tour, we also passed through some manufacturing divisions where we saw traffic light systems being manufactured. Apparently the R&D groups, engineering groups and prototype development groups were not separated spatially.

Following the technical meeting we were driven for about one hour to the Itami Dai-ichi Hotel where we had a truly magnificent dinner. From the research laboratory came Dr. Tada, Mr. Kawashima and Mr. Hitotsuyanagi, and we were joined at the hotel by Dr. Akio Hara, Director of Sumitomo Electric Industries at Itami and Mr. Shoji Yazu, Deputy General Manager of the Itami Research Laboratory. In addition to the research laboratory in Osaka, there are research laboratories at Itami, Yohokama and Ibaraki. The discussion at

dinner was quite philosophical and was most interesting for all.

We summarize here a few high points of this conversation. Sumitomo Electric is determined to be the best in everything they do. This company philosophy has a major impact on creating the proper environment for their aggressive and excellent R&D program. The Sumitomo management is out to hire the best technical people available from universities. The Sumitomo Electric managers feel that, in general industry gets very good people and can compete very favorably with the university and government sectors for talent because a job in a top company commands high prestige. In hiring people, Sumitomo Electric looks for clever people, not necessarily specialists in areas of interest to the company. For example, Dr. Tada, who manages the Sumitomo Basic Research Program, is a graduate of Kyoto University in Nuclear Physics, and a very impressive gentleman. The Sumitomo managers have some respect for university researchers. They feel that the universities attract some bright people and the best universities have high quality faculty. However, poor resources, and poor facilities at universities hamper their efforts. The Sumitomo Electric managers also feel that the universities are getting better, and the company is therefore using more university faculty members as consultants than in the past.

The Sumitomo Electric managers are quite mindful of the importance of large scale, government supported projects in keeping the Japanese superconductivity industry alive and healthy. On the one hand, the company managers speak of their independence, and how effective they are without help from anyone. This attitude seems very common in Japanese industry. Nevertheless, to an outsider the technical benefits that Sumitomo Electric and other superconductivity companies have received from national laboratories such as NRIM and ETL are very significant. Long-term contracts received from ETL and JAERI have been very important for sustained superconductivity R&D efforts at Sumitomo.

The Sumitomo Electric goals for use of superconducting materials are to have J_c values 3 orders of magnitude higher than Cu. In this race, they expect to be able to achieve $J_c \sim 10^5$ A/cm² in their high T_c tapes by the end of 1989. The Sumitomo management is very proud of their achievements in superconducting materials R&D to date, including their work on single crystals, thin films, wires and tapes. They were also proud of their work on organic superconductors, especially the large single crystals they have made.

The company managers feel that they have a very good opportunity to do R&D, including very long range R&D. The Japanese shareholders are very patient and do not emphasize short term financial results. The shareholders believe that their companies will go on forever, and perhaps for this reason shareholders are willing to invest with a very long term horizon. In Japanese industry, the employees are the heart and soul of the company, and are the

major concern of management, not the shareholders.

In discussing foreign workers in Japanese industry, the Sumitomo Electric managers expressed an interest in having a few visiting foreign scientists in their research laboratories to enhance their creativity. We heard similar interests in almost all the laboratories we visited. The managers, however, were not interested in foreign workers in their Japanese plants. They were concerned that foreign workers have a different culture and that the Japanese islands were already too crowded with Japanese people.

B.3.11 Toshiba

M.S. Dresselhaus

We (John Hulm, Brian Maple, Paul Horn, Rod Quinn and Mildred Dresselhaus) arrived at the Toshiba Central Research Laboratory about half an hour late because of the rain and the slow traffic. Therefore Dr. Kiyoshi Nagai, senior Vice President and Director of the R&D Center, who was planning to greet us and give us an overview of the laboratory, could not wait any longer. Thus we were instead received by our host Dr. Hiroyasu Ogiwara, a "Fellow Scientist" of the Toshiba R&D Center who would be classified as a Toshiba Fellow in the U.S. industrial research laboratory system. After the usual introductions and exchange of business cards, we were shown a film of the Toshiba businesses and their R&D focus. Since Toshiba is a very versatile, high tech company, their R&D activities are diverse, including microelectronics, telecommunications and information processing, optoelectronic devices, high definition TV, magnetic resonance imaging system, mechatronics, large scale energy systems, and new materials.

Following the movie, Dr. Ogiwara made a presentation on the superconductivity research at Toshiba. Basic superconductivity studies were carried out in two laboratories: the advanced research laboratory, which was a new laboratory devoted to high- T_c superconductivity and biotechnology research, and the energy sciences and technology laboratory where most of the low- T_c studies were done, with a little high- T_c work also being done there. The applications work was carried out in several other laboratories, with projects connected with the magnetic resonance imaging systems being carried out in the Medical Engineering Laboratory of the Medical Systems division. Of the 500 MRI systems that have been sold in Japan, 30% of these were produced by Toshiba, with each MRI system containing a superconducting magnet. Superconducting magnet development was carried out in the Heavy Apparatus Engineering Laboratory and materials for superconducting wire and other applications were under study in the New Materials Engineering Laboratory, while other uses for supercon-

ducting magnets such as for reducing convection in the growth of high quality GaAs boules were pursued in the Electron Device Engineering Laboratory.

Recently the Toshiba Corporation has considered the commercialization of products based on superconducting technology in great detail, by convening a corporate R&D Strategy group reporting to the Executive Board of the Toshiba Corporation, and chaired by one of the Senior Executive Vice Presidents. This corporate R&D strategy group consisted of three working subgroups. These subgroups started meeting in early 1987 after the advent of high- T_c superconductivity, and met intensively for a year, after which time it was decided that high- T_c superconductivity was not important for the business at present, and should be pursued only at the research level. To orchestrate this basic research program, a new research laboratory was established. There are about 50 people now working at Toshiba on superconductivity; 20 on high- T_c and 30 on conventional superconductivity.

Following the overview presentation on superconductivity research by Dr. Ogiwara, the next presentation was given by Dr. Osamu Horigami, Senior Manager of the Energy Science and Technology Laboratory. He reported on the activities of about 25 people working on Cryogenic Engineering, Superconducting Magnet Systems and Superconducting Materials Development. This group has been involved with such projects as developing superconducting magnets for magnetic resonance imaging, magnetic levitation for trains, magnetohydrodynamic generators for ship propulsion using seawater and magnets for single crystal growth of semiconducting crystals. Advanced design work for superconductivity products is done by Dr. Horigami's group. This group was also involved with research aimed at producing higher magnetic fields in superconducting magnets through improved materials and design, using such techniques as adding Ti to Nb_3Sn using a tube method and by bringing the filament diameters of the superconducting wire down to smaller and smaller dimensions. Toshiba researchers now have reliable processes for producing superconducting filaments at the $0.44\mu m$ level, and were now developing the technology for filaments at the 700\AA level. They showed us some impressive results for Ti doped Nb_3Sn materials achieving current densities of $400A/mm^2$ at 23T. By using a Nb tube rather than a bronze method they had previously used, they were able to eliminate an annealing step, thereby reducing costs and improving performance. The superconducting magnet work of this group is truly world class. The continuity of support and the challenging engineering projects have provided a superior working environment and motivation for this Toshiba group.

We next heard a presentation by Dr. T. Miura of the Advanced Research Laboratory, who spoke to us on several research topics: the search for new high- T_c superconducting materials, improving existing high- T_c materials, and

thin film growth. This group is also involved with the properties measurements and the technologies of preparing junctions and in patterning these junctions. For high speed electronic devices and for telecommunications, low temperature processing, smooth surfaces and high surface stability is needed. The film quality and surfaces of the $\text{YBa}_2\text{Cu}_3\text{O}_7$ on MgO and SrTiO_3 substrates they showed us looked good. They also showed us some tunnel junction and patterning results. They were working on both the YBaCuO and Bi systems with a variety of techniques (3 target sputtering, MOCVD, MBE). In fact, the major emphasis of the thin film program seemed to be systematic studies of different approaches to thin film growth to see which method had the best characteristics for specific applications.

Following Dr. Miura's presentation, Dr. H. Yoshino reported on other high- T_c superconductivity research including superconducting properties and structural modulation of the $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ system and the growth of large single crystals of these Bi compounds. This group was studying the effect of the substitution of Ca by Y and the origin of the structural modulation effect in the Bi compounds. The large single crystal was grown by the self flux method and Dr. Yoshino told us that the secret of success in the crystal growth was the slow cooling of $1^\circ\text{C}/\text{hr}$. The samples were removed from their containment with a laser. Dr. Ando claimed that the growth of good single crystals did not require fancy apparatus, but rather a high degree of attention and care.

This group has done some very good work with regard to the substitution of Ca^{2+} by Y^{3+} . In this system, since the radius of the two ions is almost the same, it was assumed that the crystal structure remains the same as holes are added. One achievement they were proud of was the first report of a superconductor to semiconductor transition in the $\text{Bi}_2\text{Sr}_2\text{Ca}_{1-x}\text{Y}_x\text{Cu}_2\text{O}_{8+\delta}$ system as x is increased, this transition occurring without passage through a metallic non-superconducting phase. Similar systematic work on this subject was also seen at Tohoku University where Lu rather than Y was used. With this system they carried out careful phase diagram studies and were the first to clarify the relation between the Cu concentration and T_c upon Y doping. Dr. Yoshino showed some very nice high resolution TEM pictures for their modulation structures, and results were also shown relating superconducting properties to the changes in lattice parameter and Pb doping. They showed that for samples with high- T_c , the Meissner effects were sharp. They then gave us a collection of interesting publications.

Following these presentations we had some discussion. During these discussions, they showed us early results on wires and tapes, which they explored soon after the advent of high- T_c superconductivity. But they have not pursued this further because of their strong belief that this is the time for basic research on high- T_c materials. The Toshiba people feel that major electronics applica-

tions are far away. They watch the work at Nippon Steel on increasing the J_c for wires and tapes using the quench-melt method, but they feel that all the laboratories in Japan are still a long way from making a commercial wire. Dr. Ogiwara himself feels that there are two kinds of companies: newcomers to superconductivity, who are very excited about the new high- T_c materials and are not sensitive to the realities of making reliable superconducting devices based on superconducting wires, and companies with a lot of experience with superconducting machinery, and these latter companies are more cautious about their superconducting R&D programs. The Toshiba people explicitly mentioned Professor Tanaka as an enthusiast who may not be too realistic about the commercial side of superconductivity. In the meantime, Toshiba is deeply committed to superconductivity R&D, with half of the funding coming from corporate funds, and half from the manufacturing divisions, thereby reinforcing technology transfer. Toshiba has surprisingly little interaction with NRIM, but will interact and compete with other applied superconductivity R&D programs like with Hitachi on the table top synchrotron orbital radiation machine. In this case, Hitachi is designing a machine based on a superconducting magnet while Toshiba's machine is based on a conventional non-superconducting magnet. We also heard about some cooperation between Toshiba and Sumitomo Electric on designing a small refrigerator for liquid helium production, for use on a Maglev system based on conventional superconductors. Professor Tanaka is however of the opinion that Maglev equipment will have to be operated at 77K to be cost effective, so he is looking for high- T_c superconducting magnets and energy storage systems for Maglev applications.