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# 日本の超伝導産業における研究開発コンソーシアムと共同関係

# Research and Development Consortia and Cooperative Relationships in Japan's Superconductivity Industry

ジェラルド・ハネ
米国ハーバード大学科学技術政策部

Gerald Hane
Science, Technology and Public Policy
Harvard University, U.S.A.

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First Theory-Oriented Research Group
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# I. INTRODUCTION

When Koichi Kitazawa and Paul Chu independently announced confirmation of the high temperature superconductivity phenomena at the Materials Research Society Conference on December 4, 1986, they ignited the international development of a new field. It was an unanticipated and a major breakthrough which offered an array of possibilities and questions to be answered. How high would the temperature go? Could these materials be processed into useful devices? What was the cause of the phenomena?

For science, the discovery posed a challenge to well established theories of the mechanisms of superconductivity. Accepted theories did not predict this phenomena and did not provide a guide of how to proceed. For the industry, and for consumers, the discovery offered new hope for the possibility that superconductors might yet come into widespread common use, affecting a wide range of activities ranging from vehicle transportation, to energy conversion and storage, to information processing, to medical and material diagnostics.

The sudden emergence of high temperature superconductivity provides an opportunity to examine the response of public and private institutions to a major unexpected breakthrough which at least for a brief time captured the attention of scientists, industrialists, and policymakers. It provides a chance to see how policies take shape as various arms of the bureaucracy vie for a role in its development, and as various firms and laboratories move to position themselves in the industry. And it provides a chance to view the use of cooperative R&D as institutions move to strengthen themselves quickly in this area.

High temperature superconductivity did not, however, occur in a technological vacuum as there did exist an established superconductivity industry in Japan which had developed over the previous 20 years. It was an industry which was reared over a history of large engineering projects, and is a history which is itself revealing of the uses of consortia for technology development.

In this chapter I will be examining the role of government policy in support of innovation and the role of R&D alliances through research and development projects in both high temperature and traditional low temperature superconductivity. Throughout this section the history, analysis of the industry, and case studies area all conducted with an intent to examine how these projects are created, how they are organized and executed, and what impact the activities have on the technology or industry.

Dividing these projects between the high temperature and low temperature cases allows a contrast of the use of consortia to support projects which are primarily a technological or engineering challenge, those involving low temperature superconductivity (LTS), and projects which are a scientific challenge, those involving high temperature superconductivity (HTS). Examining the low temperature cases also allows for an opportunity to view the influence of differing technological characteristics such as scale and complexity on the operation of consortia.

This report is divided into nine sections. Following this introduction, the second section provides a brief introduction to the technology, its applications and potential applications, and the problems faced in its development. The third section presents a discussion of the history of the superconductivity industry in Japan up to 1986. This section will illustrate the early role of government programs and consortia in pursuing superconductivity, relationships established, and the development of the major laboratories and technologies. The fourth section contains a review of the status of the industry and of industrial relationships at the time of the discovery of HTS. This is followed in the fifth section by an examination of the timing and magnitude of the response of the industry and of the government to the HTS discovery, asking how well the latter seems to support the former. After this review the discussion will move to an analysis of specific cases in collaborative R&D in Sections Six and Seven. The two cases in HTS collaboration focussed on here are the International Superconductivity Technology Center (ISTEC) and the Multi-Core Program. The seventh section is an analysis of cases from LTS R&D. These cases provide the opportunity for examining in more detail the issues of formation, organization, and impact in a less fevered environment. In the eighth section I touch on the issue of collaboration in R&D generally in superconductivity to examine more broadly how collaboration has been used to promote innovation, and conclude with a general summary in Section Nine.

## II. WHAT IS THE TECHNOLOGY

To understand the technical side of why science and technology policies are implemented, what effect they have on technological progress, and in particular to understand what incentives the technologies pose for collaboration, an understanding of the substance of the science and technology is essential. In this section I will provide a brief description of superconductivity and superconducting technologies to give technical perspective for the analyses which follow. I will also introduce the range of uses of this technology and their promise should use of high temperature materials become realized.

Superconductivity is the complete absence of resistance to the flow of an electrical current. When electricity passes through conventional materials, the flow of the current meets with resistance and some of the energy in the current is dissipated as heat. The better the conductive properties of the material, the less the resistance. However, all conventional materials pose some resistance. In superconducting materials, the resistance is zero and electricity is able to move with perfect efficiency. To realize these benefits, however, the materials have to be dropped to very low temperatures. This complete loss of resistance is extremely appealing as it means that no energy is lost in the material, that the heat generated by conventional conductors can be completely eliminated, and that very strong magnetic fields can be generated by much smaller magnets.

This phenomena was first recorded by Heike Kamerlingh Onnes in 1911 while he was conducting experiments on the behavior of metals at very low temperatures. At the time, he was not "searching" for superconductivity, as the phenomena had not been hypothesized, but was competing with fellow scientists to achieve experiments at lower and lower temperatures through the liquifaction of rare earth gases. Thus it was not the breakthrough of discovering superconductivity which Kamerlingh Onnes was pursuing, but the breakthrough of being the first to liquify helium, which he accomplished in 1908 at the University of Leiden. The liquifaction of hydrogen allowed him to conduct materials experiments at temperatures lower than had ever been conducted before, and it was in the midst of these experiments that he discovered strange changes in the properties of mercury, which he later verified and termed "superconductivity."

Pondering the implications of this possibility in his early writings, Kamerling Onnes commented that "the miniature coil ... may prove to be the prototype of magnetic coils ... by which in the future much stronger and ... more extensive fields may be realized than are at present reached in the interferrum of the strongest electromagnets."[1]

High field magnets have in fact turned out to be the principal use of superconductors. Applications being developed include those in energy (experimental fusion magnets, electricity generation, and energy storage systems), high energy physics experiments (accelerators), transportation (magnetic train levitation, electromagnetic ship propulsion), and medicine (MRI and NMR). In addition to these applications, the zero resistance property of the superconductors has attracted attention for computer applications and signal processing, and a phenomena unique to superconductors known as the Josephson effect has made it attractive for very sensitive sensor measurements.

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[1] David Larbalestier, et. al., "High-Field Superconductivity," Physics Today, March 1986, pp. 24-33.

Why does superconductivity require such low temperatures? Stated simply, it is because only at these temperatures are the atoms in a crystalline lattice quiet enough not to disturb the flow of the superconducting electrons. As temperature increases, the atoms begin bouncing around more, and thereby interfere with the path of electron flow.

Until 1986, superconductivity was only observed when materials were cooled down to extremely low temperatures. The elemental superconductors would only exhibit this property at temperatures below 10 K, and the various compounds synthesized over the subsequent decades would not climb much higher. Niobium nitride was found to superconduct up to 16 K in 1941 and in the forty five years that followed, the critical temperature had only risen to 23 K with the synthesis of niobium-germanium by John Gavaler in 1971.

The challenge in increasing the use of superconducting materials, however, is not just raising the temperature but forming the materials into wires, films, or balls, that must be capable of carrying useful currents and operating, often, in magnetic fields. For magnet applications, currents typically demanded are on the order of 10,000 to 20,000 A/cm$^2$ under fields ranging between 1 to 8 telsa (1 telsa (T) is equal to 10,000 Gauss, with the typical strength of a refrigerator magnet being less than one gauss.)

If a superconductor is fed too high a current or exposed to too high a magnetic field it will cease to be superconducting. To understand why, it is helpful to understand that a superconductor responds to the presence of a magnetic field. A characteristic unique to superconductors is their ability to completely exclude magnetic fields that exist in the conductor. This effect, discovered by Walther Meissner in 1933, and hence named the Meissner Effect, means that the magnetic field generated by the superconductor resides *entirely outside of the conductor.* This was a significant step in understanding the behavior of the materials, as it pointed out that superconductivity involved not just a change in electrical behavior, but a change of thermodynamic states. However, excluding the magnetic field requires energy, and it is when this required energy becomes too great that the ability to superconduct disappears.

Traditional superconductors fall into one of two classes based on their behavior. The are either Type I or Type II superconductors. The early elemental superconductors were Type I superconductors. In these materials, there exists perfect diamagnetism until a critical magnetic field is reached. Beyond this value, the material returns to its normal state. Type II superconductors comprise many of the compounds synthesized over the past four decades, such as the niobium compounds, which tend to reach higher temperatures than the elemental materials. In these materials magnetic fields can penetrate the material in an orderly array through the formation of vorticies.

Thus in a Type I material, the current only flows at the surface of the wire. Any current that would flow in the wire would create a magnetic field and would thus be expelled. This expulsion, however, requires a bit of energy in the form of magnetic screening currents. The greater the field, the greater the screening energy. Thus when too great a field is applied, the energy level in the superconductor exceeds that in its normal state, so the material converts to the lower energy level and loses its superconductivity.

In a Type II superconductor the presence of a magnetic field can cause the superconductor to enter what is known as a mixed state. Predicted and demonstrated by Soviet physicist Alexei Abrikosov in 1957, the presence of the mixed state allows the materials to maintain its superconductivity in higher magnetic fields by reducing the amount of energy needed to enable the superconductor to expel the magnetic field.

The magnetic field penetrates the superconductor through cylindrical cores which are known as vortices, with each such vortex carrying one quantum flux. Each vortex creates a little magnetic field and interacts with the fields generated by other vortices. The greater the magnetic field that needs to be counteracted, the larger the number of vorticies. When the material can no longer accommodate new vorticies, it returns to its normal state and superconductivity disappears.

The mechanism defining critical current is also slightly different in the case of a Type II superconductor. The movement of the current in the wire, where there is also a magnetic field, creates a Lorentz force which causes the vorticies to move at right angles to the flow of the current. This motion causes a loss of energy in the form of heat, which is effectively a resistance to the current, and which causes the material to lose its superconductivity. To get around this phenomena, know as "flux creep," researchers have developed techniques to make it immobile, to "pin" the flux, and thus allow substantial currents to pass without a loss of superconductivity. Common techniques are to add impurities or stress the material, creating grain boundaries which act to pin the vorticies. An interesting implication of this is that a superconducting material that is perfect, without impurities or grain boundaries would not be able to pass a current without losing its superconductivity. This phenomena of flux creep, it turns out, also becomes a key issue in the development of practical high temperature superconductors.

The principal limitation to wider use of superconductors has, however, been temperature. Whereas critical current and critical magnetic field strengths can be improved through processing techniques, temperature is a property of the material. With the highest temperature material only reaching 23 K, the bulky and costly refrigeration requirements prove a major handicap to diffusion.

Reducing or eliminating this handicap has been the quest of superconductivity researchers since its discovery. The sudden possibility that this might be achieved through an entirely different class of materials was why there was so much excitement surrounding the Bednorz and Mueller discovery.

The discovery of superconductivity in a pervoskite material was exciting for a number of reasons. It revived the hope of finding a material that might superconduct at room temperatures. Secondly, it revealed a phenomena that was new to an entire class of materials, and was achieved in the absence of an accepted theory of why this might be occurring. It thus opened the possibility that an entirely new phenomena had been discovered. And thirdly, it involved a class of material in which most traditional superconducting manufacturers were not involved, which required little capital investment to enter, and which thus provided an attractive opportunity for firms wanting to diversify.

A material that can superconduct at room temperatures has been a hope of industrialists since the phenomenon's discovery. It would mean the elimination of bulky and costly refrigeration requirements and the widespread use of the superconductivity to dramatically reduce electricity conversion and transmission losses, to provide powerful, compact magnets and energy storage systems for stationary and mobile uses, to enable the widespread use of ultra-sensitive sensing technologies, to enhance signal and information processing, as well as to find application in uses yet to be conceived.

In the realm of theory, pervoskite superconductivity appeared to be an exception to the well established theory of the superconductivity mechanism proposed by John Bardeen, Leon Cooper and Robert Schrieffer in 1957. The essence of this theory is that the superconductivity comes about when electrons form pairs to pass through a material. Normally, electrons would repel each other as they carry a common negative charge. In the case of metallic superconductors, however, the electrons are found to form pairs. These pairs are formed as the result of an interaction between free electrons and vibrations in the lattice of the material, a phenomenon known as electron-phonon interaction. Here the interaction of the electron and the lattice results in a slight distortion in the lattice which tugs on neighboring ions. The tug on the ions causes a slight polarization, and the resultant concentration of positive charges attracts a new electron. When these two electrons bind together, they have a lower energy level than if they remain independent, and thus represent a thermodynamically more stable condition. The lowest energy level is achieved when all of the pairs behave in the same way, when they have the same wave function. And it is when the are all in lock step that superconductivity arises. Whether this is the mechanism occurring in the new high temperature superconductors is unclear.

Thirdly, the new superconductors were ceramics and the traditional firms in the industry had little experience with this material. Additionally, the costs of synthesizing and experimenting with the material were low, so firms outside of the traditional industry had low barriers to entry. The new material provided an attractive opportunity for diversification.

## The Potential Impact of HTS - Market Studies

The excitement over the unexpected discovery of higher temperature superconducting materials also led to a rush in speculation about the size of the impact of this new technology. Was it possible to measure the potential size of the impact?

One dimension which can be estimated with a number, and in which firms are most interested, is the market potential of applications of higher temperature materials. A major question, of course, was how high one expected the critical temperature of the material to rise. If is was assumed temperatures would plateau in the range of liquid nitrogen, then most projections were for some incremental expansion of the market. If, however, the materials were usable at real room temperatures, then the range of new and expanded applications could be dramatic.

The earliest estimates of market potential were released by the Nomura Research Institute and by Sumitomo Electric Corporation. Influence by the early excitement surrounding the discoveries, and hearing rumor that room temperature superconducting materials had been discovered, Nomura projected that a truly room temperature superconducting material would be applicable in a few years. Thus they estimated that the market for superconducting materials would grow to 6 trillion yen by the year 2000 and 17 trillion yen by the year 2010.[2] This projection is shown in Figure 1.

This projection drew a great deal of excitement at the time as it amplified the sense that high temperature superconductivity was bound for a major impact on society. The estimate was not, however, based on a specific breakdown of the markets.

Sumitomo Electric soon followed with a projection which more explicitly identified the technologies likely to be most effected and divided markets into those affected by materials which would be cooled by liquid nitrogen (77 K) and materials which could operate at room temperature. Their estimates were more modest than the Nomura projections, with a market of 0.5 trillion yen for materials at 77 K, and 5 trillion yen for room temperature materials.

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[2] "Chodendo Gijutsu no Genjo to Doko," NRI Repoto, No. 125, July 13, 1987, p. 17.

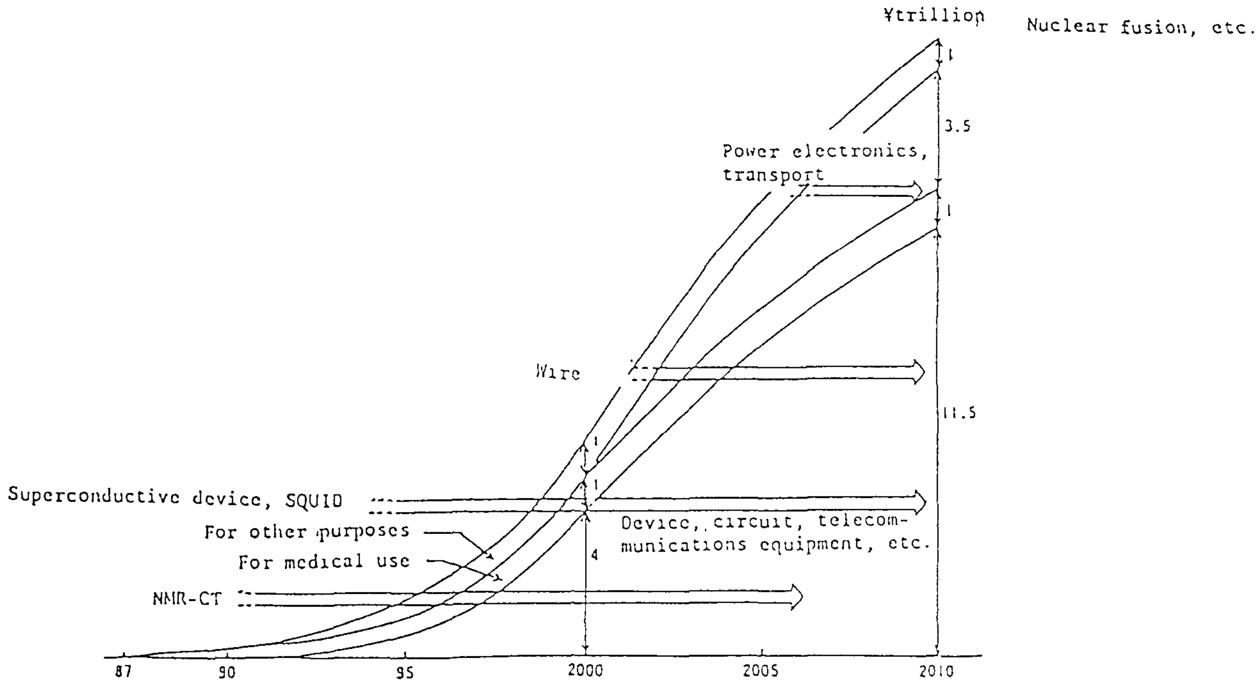

Figure 1. Projected Growth of the Superconductivity Market After the Discovery of HTS (Material based on NRI Repoto, No. 125, July 13, 1987, p. 17)

After the excitement had settled down, more thorough and technically thoughtful analyses were conducted by a number of other firms including the Nikkei Research Institute, the International Superconductivity Technology Center (ISTEC), and Mitsubishi Research Institute.

In these studies each of the technologies to which high temperature materials were likely to be applied were identified and performance improvements estimated. Uses identified by the Nikkei Research Institute are shown in Table 1.

A summary of the estimates from the first two studies are presented in Table 2. The Mitsubishi Research Institute study is proprietary so the figures cannot be published here, but in general order of magnitude they are in agreement with these public studies.

The largest jump in the Nikkei study is projected to occur in the transportation sector, a 9.5 fold increase. This is primarily due to a very optimistic figure assigned to the development of all electric vehicles charged with superconducting energy storage rings. This use alone, they project, will jump 1,910 billion yen with the application of materials operating at 77 K to 29,910 billion yen with room temperature superconductors, a 15.7 fold increase. Also weighing heavily in this projected increase are the electromagnetic thrust ship, increasing from 2,365 billion yen to 4,865 billion yen, and the magnetic train levitation, increasing from 80 billion yen, to 2,645 billion yen.

The electronics sector exhibits the next largest potential expansion, increasing 5.7 times from 442 billion yen to 2,537 billion yen. The largest contribution in this sector comes from the expanded use of zero-resistance substrate components, projected to increase from 196 billion yen at 77 K to 4,940 billion yen with room temperature superconductors. Also ranking high in the increase were zero-resistance LSI circuitry, rising from 205 billion yen to 3,710 billion yen, an 18 fold expansion, and superconducting LSI, growing 29 fold, from 76 billion yen to 2,223 billion yen, and superconducting supercomputers, increasing in application from zero to 1,265 billion yen per year.[3]

The above are applications which are primarily extensions of existing technology. However, as The Committee to Advise the President on High Temperature Superconductivity has pointed out, this is a new materials phenomena and it may well be that the most significant applications "cannot be identified today."[4]

## III. THE DEVELOPMENT OF A SUPERCONDUCTIVITY INDUSTRY IN JAPAN

To more fully appreciate the rise of high temperature superconductivity research in Japan, it is helpful to have some understanding of how the low temperature industry developed. How important were government policies and programs to the development of this industry? Through what path did the principal research centers evolve? What were the relationships developed between the firms and the government or among the firms themselves? Who were the motivators of the projects and the policies? How well poised

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[3] Chodendo Gijutsu ga Sangyo Shakai ni Ataeru Inpakuto ni Kansuru Kenkyu Hokokusho," Nikkei Sangyo Kenkyusho: Tokyo, June 1988, p.41.

[4] The Committee to Advise the President on High Temperature Superconductivity, High Temperature Superconductivity: Perseverance and Cooperation on the Road to Commercialization, Washington, D.C: White House Science Council, 1988, p.7.

Table 1. Potential Applications of Higher Temperature Superconducting Materials

Electric Power

- Electricity Power Generation
- Transmission Wire
- Transformer
- Large-Scale Electric Power Storage
- SMES for Load Levelling
- MHD

Transportation / Industrial Machinery

- Magnetically Levitated Train
- Magnetic Propulsion Ship
- Electrically Powered Ship
- Electric Car
- Motor
- Magnetic Separation Systems
- Electromagnetic Discharge Equip
- Free Electron Laser

Electronics

- IR Sensor
- Zero Resistance Substrate
- Zero-Resistance LSI Circuitry
- Superconducting LSI
- Superconducting Supercomputer
- Magnetic Shielding
- Small-Scale SOR
- Low Loss Communication Cable
- Telecommunications Signal Processor

Medical

- NMR-CT
- Small-Scale Cyclotron
- SQUID

Research Equipment

- Oscilloscope
- Voltage Standard Equipment
- Electron Microscope
- Large Scale Particle Accelerator
- Sputtering Target Material

Table 2. Projected Markets for HTS Material Applications (billion yen)[5]

| Category of Use | Liquid Nitrogen Temperature | Room Temperature | Relative Increase |
|---|---|---|---|
| Electric Power | 282.1 (18.2%) | 637.5 (6.0%) | 2.3 |
| Transportation/ Plant Machinery | 769.4 (49.7%) | 7,340.3 (69.0%) | 9.5 |
| Medical | 50.6 (3.3%) | 85.9 (0.8%) | 1.7 |
| Electronics | 442.0 (28.5%) | 2,536.9 (0.3%) | 5.7 |
| Research and Other | 5.1 (0.3%) | 34.0 (0.3%) | 6.7 |
| Total | 1,549.2 | 10,633.6 | 6.9 |

was the industry to exploit the new high temperature materials? To provide insight into these questions, a brief history leading to the discovery of HTS is presented below.

In this history we will see that the government was critical to the formation and nurturing of the industry through both its technology promotion programs and its procurements. This was aided by the serendipitous timing of important developments overseas, by the multiple uses of this technology, and by the fact that the principal uses considered were all applications in which the government was a main customer.

We will see that the principal firms today in wire development and in systems development are those that have been selected for participation in government projects in superconductivity since the outset of its development in Japan, 25 years ago. And we will see that single actors were never allowed to dominate the government projects. Instead, three key actors of similar commercial capabilities were commonly chosen throughout the history of the technology.

Regarding inter-firm relations, we will see that collaboration can occur when there is a technical need and government imperative, but that the firms are nurtured as a competitive set more than a cooperative one. Technology transfer from outside organizations will be seen to be important in the birth of this field in the private sector, but the transfer is from the public sector. Evidence of competitive firms collaborating rather than competing will be more the exception than the rule.

Regarding important motivators of policy, we will see that university professors were key in gaining salience for this field and its technologies, and in establishing the initial

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[5] "Chodendo Gijutsu ga Sangyo Shakai ni Ataeru Inpakuto ni Kansuru Kenkyu Hokokusho," Nikkei Sangyo Kenkyusho: Tokyo, June 1988, p.50.

information network. We will also see that although the principal negotiations occurred between the bureaucracies, firms, and advisory committees, the role of the politicians can be critical for large projects. Large technology projects, like large infrastructure projects, can be are as susceptible to pork barreling in Japan as in any country.

And although the industry was small, we will see that these firms were at the international state-of-the-art in low temperature superconductivity technologies at the time of the discovery of the oxide phenomena.

## The Development of a Superconductivity Science and Technology Base

Cryogenics research in Japan is typically traced back to the work of Professor Hantaro Nagaoka at the University in Tokyo.[6] Early in 1902, Prof. Nagaoka purchased an air liquifier from the Linde Company of Germany and was the first to demonstrate air liquifaction in Japan. At this time, the Japanese government was placing a high priority on learning from the west, particularly in industry and technology, and professors were supported to act as the vehicles of information transfer. As a result, in 1910, Prof. Nagaoka was able to attend a conference of the International Association of Refrigeration (founded at Kamerlingh Onnes' initiative) in Vienna, and impressed by the advanced level of the technologies overseas, returned to Japan as a principal promoting the development of a domestic cryogenic industry.

In 1912, Prof. Nagaoka sent one of his students, Masao Kinoshita to Europe where, for 15 years, he conducted research in cryogenics and superconductivity. When returning to Japan, to the Institute of Physical and Chemical Research (known today as RIKEN), however, he found that he was not able to obtain a hydrogen liquifier for his experiments. Hydrogen compressor technology did not exist in Japan and importation was beyond his budget, so he was only able to lecture about the discovery of this new phenomena abroad. It was not until the 1930's that the first hydrogen liquifier became available in Japan, a unit purchased from Germany and installed at the Research Institute for Iron, Steel & Other Metals at Tohoku University. Thus initial leaders in superconductivity came from this laboratory in northern Japan, and included Dr. Shinichi Aoyama (who had been sent to Leiden in the late-1920's), Eizo Kanda, and Tadao Fukuroi.

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[6] K. Oshima and Y. Aiyama, "The Development of Cryogenics in Japan," Chapter 14 in History and Origins of Cryogenics, ed., R.G. Scurlock (Southampton University), to be published.

Throughout the 1940's and 1950's, research in superconductivity remained an academic interest, pursued at a low level of activity, largely because of the difficulty of accumulating the foreign exchange needed to buy liquifaction equipment from Europe. In July of 1952, the first helium liquifier in Japan was installed at Tohoku University. It was a Collins liquifier (named after its discoverer S.C. Collins of M.I.T.) manufactured by Arthur D. Little, Inc., and was purchased with funds from the Ministry of Education with the approval of GHQ Occupation Forces. However, the Ministry was not willing to release funds for the purchase of more than one machine so this laboratory also had to serve as a national liquifaction user center.

In 1958 a team at the the Institute of Science and Technology of the University of Tokyo, under the leadership of Prof. Kei-ichi Oshima, successfully demonstrated the first domestically produced helium liquifaction device. It used a cascade design and was developed in close collaboration with a major cryogenics manufacturer, Nippon Sanso. In the same year, the government purchased its second helium liquifier from Arthur D. Little, Inc. for installation at the Electrotechnical Laboratory (ETL) of the Ministry of International Trade and Industry, and in 1959 a third was unit was purchased by the R&D Center of Toshiba Corporation.

By the late 1950's companies also began to flirt with superconductivity, with firms such as Mitsubishi Electric and Sumitomo Electric initiating development work into a Collins-type liquifier. In December of 1959 Mr. Ogino of Mitsubishi Electric succeeded in developing an expansion cycle system, and by 1963 this had been developed into a commercial device. With a flow rate of 8 liters/hour it was large enough for small scale laboratory experiments. The first domestic sale was to the University of Tokyo, with a second going to the Electrotechnical Laboratory. However, not only were these machines still quite expensive, they were expensive to operate. All of the helium had to be imported, and at this time helium was both difficult to acquire and very expensive, costing 10,000 yen/liter.

During this period of technology development in Japan, which continued into the mid-1960's, the testing of "extreme environments" became a popular theme among research laboratories. This was reflected by the slogan popularized at this time: *"Cho he no Chosen,"* (Challenge the Extremes.) Under this banner, laboratories explored phenomena associated with extremes of temperature, pressure, material strength, material purity, etc.[7]

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[7] K. Furuto, "Furukawa Denko 'Chodendo kenkyu kaihatsu gurupu,'" Teion Kogaku, Vol. 23, No. 4, 1988, pp.225-228.

Not until the early-1960's, however, were superconductors formed which could carry the current necessary to be used in practical devices. In 1961, Eugene Kunzler's research team at the Bell Laboratories succeeded in creating a $NbSn_3$ magnet which produced a field of 88,000 gauss (8.8 telsa) with no resistance to direct current in the windings. Bell researchers also synthesized a niobium zirconium alloy which appeared easier to process into wires. Then in 1962, Ted Berlincourt at Atomics International found that niobium-titanium had even better ductility for wire forming and was very durable in strong magnetic fields. This was to become a principal choice for the applications that were to develop later.

Important advances were being made successively now overseas, but information diffused slowly through Japan as the mechanisms for dissemination which proliferate today, the associations and frequent symposia, were not available then. On June 30, 1961, under the leadership of Professors Kanda, Oyama, Oshima, Hatoyama, and Kadona, 45 individuals were assembled to initiate a Cryogenic Engineers Club *(Teion Kogaku Danwakai)*, to share information about the developments overseas.[8] The group was first administered out of Prof. Oshima's office in the Nuclear Engineering Department of the University of Tokyo.

It was also in this period that K. Mendelssohn wrote to Prof. Oshima proposing that Japan sponsor the first major international liason between engineers and scientists in the field: that they sponsor an International Cryogenic Engineering Conference. To organize such an activity and to recruit the needed funding, the group realized that the official backing of the government would be necessary and so decided to create a formal organization. In March 1966, the Cryogenic Engineering Association was formed with the approval of MITI and the Science and Technology Agency and had an initial membership of 150 members. Prof. Oyama was its first chairman. In April 1967, the First International Cryogenic Engineering Conference (ICEC-I) was held in Kyoto, Japan. Several researchers interviewed noted that it was not until this conference that news of the commercial advances in superconductivity became generally known in the country.

In these early years, the transfer of personnel and ideas from a variety of sources was key to the development of the industry. Universities, national laboratories, and foreign sources played an important role in introducing this field into corporate laboratories. In 1958, Dr. K. Nakamura at Nihon University left to initiate

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[8] Gohei Kanara, "Teion Kogaku Kyokai Setsuritsu, to Oshima Sensei," Teion Kogaku, Vol.24, No.1, 1989, p.4, and K. Oshima and Y. Aiyama, op.cit.

superconductivity research at NEC.[9] In the early-1960's, Dr. T. Doi of Hokkaido University helped Hitachi develop wires out of superconducting materials and Dr. S. Maeda moved to Hitachi from Tohoku University to continue his work in superconductivity and magnetics. Also in the early-1960's, Dr. T. Komata came to Mitsubishi Electric from Osaka University to initiate research on superconducting materials and Dr. M. Iwamoto moved over from Tokyo University to initiate the research into magnets. At Furukawa, a researcher was sent to NRIM to learn about superconductivity in 1962 and returned a year later to start the firm's program in this area. At Kobe Steel, Dr. Asada, the then Director of the research laboratory, initiated a program in superconductivity after taking a tour of research facilities in the United States in 1964. There he learned about progress made with Niobium-based superconducting materials and upon returning to Kobe gave his staff samples he had collected, instructing them to duplicate and develop it.

It was also in 1964 that ETL developed the first superconducting magnet in Japan, one constructed of a NbTiTa material.

### - *Magnetohydrodynamic Energy Conversion*

These activities began to coalesce in 1964, when the government initiated discussions over launching a nationally funded project to develop a new form of energy conversion technology: magnetohydrodynamics (MHD). Prior to this, both MIT and Parsons in Great Britain had established MHD R&D facilities, creating a sense in Japan that this technology was one of significant promise and one which might be an important source of electricity for this nation which imports most of its energy.

MHD offers the potential of very high energy conversion efficiencies because of the extremely high source temperature. Very briefly, in this process, coal is first pulverized into powder and then heated to around 3,000 K at which temperature it becomes a plasma. This plasma moves through a very large magnet through which energy is imparted, accelerating the flow of the plasma. The fast flowing plasma then passes through electrical coils and induces a current in these coils, producing electricity. The exhaust gas is still at a very high temperature, between 1,100 K and 1,800 K , and some of this energy remaining in the gas can be captured in a gas turbine. Experiments abroad by AVCO in the early-1960's showed the possibility of efficiencies of 50-56% with theoretical efficiencies being

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[9] The NEC program in superconductivity ended in 1964, but was restarted in 1979 when a researcher was dispatched to U.C. Berkeley where he did work in lead-based superconductivity.

as high as 60-70%. The MHD system thus offered the possibility of doubling the 30% efficiencies being achieved with coal power plants at the time.

To efficiently capture the power in the plasma, however, a magnet capable of producing a very high field was required. Magnets for a useful MHD system would have to generate fields on the order of 5 to 7 telsa (T). Conventional magnets were not sufficient for this purpose but superconducting magnets held such a promise. But this was still a new technology requiring a significant investment by firms which had very little experience in the field. It was precisely for this type of technology, however, that MITI was about to introduce a new program for technology promotion.

Recall that in 1961, the Engineering Research Association system had been established by MITI to assist in the diffusion of information and the pooling of firm resources for the development of commercial technologies. Looking a step further, MITI bureaucrats realized that some potentially significant technologies would entail a risk or investment that was too great for single firms in the industry. To address this problem, the Large-Scale Technology Project (*Ogata Kogyo Gijutsu Kenkyukaihatsu Seido*) was initiated in 1966, with MHD electricity generation being chosen as one of the first themes, along with the Super-High Performance Electronic Computer and the Desulphurization Process. All three of these projects were initially scheduled for five years.

Although the project was planned for five years, its schedule was twice lengthened, first to seven years and then to ten years to allow for testing the superconducting magnets in a large MHD prototype system. Seven firms were involved in the project and the total budget for the 1966-1975 period of the program was 6.5 billion yen.[10]

Japanese industry was, however, still far behind the state-of-the-technology overseas. Given the very limited experience that firms had with superconducting magnets up to this time, producing 5 to 7 telsa magnets was a significant leap beyond their capabilities in 1966. Technology-base research would still have to be conducted on stabilization methods for superconductors and coils, material testing at low temperatures, turbo-expander characteristics for helium refrigerators, etc.

Aggressively studying developments overseas, however, significantly accelerated progress in Japan as timely progress was being made. In 1965, Dr. Z.J. Stekly and his team at AVCO in the United States had successfully demonstrated the operation of a high field superconducting magnet. In cooperation with the Argonne National Laboratory, Dr. Stekly had shown that copper cladding was an effective stabilizer for the manufacture of

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[10] K. Oshima and Y. Aiyama,, op.cit., p.18; T. Ueda, "Ogata Kogyo Gijutsu Kenkyukaihatsu Seido ni tuite," Teion Kogaku, Vol.5, No.2, 1970, p.2; and Itaru Todoroki and Kozo Fushimi, "Ogata Purojekuto Teion Bumon Keikaku Gaiyo," Teion Kogaku, Vol.5, No.2, 1970, pp.3-4.

superconducting wires for high field magnets. It became clearer with this announcement that the processing of superconducting materials might become a legitimate activity for the nation's cable and wire manufacturers. And it was a very timely development for the start of the Japanese government's first national research and development project related to superconductivity. Based on this work, Dr. Aiyama noted that "R&D work for the SCM (superconducting magnet) in the Japanese MHD project was fairly straightforward."[11] They principally had to follow the path of the AVCO success.

Despite the fact that all of the manufacturers were well behind the state-of-the-art at the outset of the program and that fundamental questions of development needed to be resolved, examination of the organization of the program shows little direct cooperation.

The overall activity was to be managed by the Electrotechnical laboratory (ETL), with Dr. Fusao Mori of ETL appointed the first Director and Dr. Kozo Fushima of ETL the second Director. ETL was responsible for developing a 1 kW MHD prototype (which used an AVCO magnet), conducting design work on a 1,000 kW MHD system, and eventually testing the operation of a 1,000 kW MHD prototype. The other tasks in high field magnet development and helium refrigeration systems were assigned to the participating firms. Mitsubishi Electric was responsible for a 7.0 T pancake coil, and Mitsubishi Electric and Hitachi, Ltd. separately developed 4.5 T saddle-shaped coils. Toshiba was given a smaller task of developing a SI magnet. Work on the helium refrigeration system was the principal responsibility of Nippon Sanso and Toyoda Machine. The primary firms and their tasks are shown in Figure 2.

Again, the organizational point here is that in spite of conditions which might have favored collaboration in development, the R&D was conducted independently by the participants. The work was contracted separately, performed in separate facilities, and generated separate patents. Several years later, MITI tried to address this issued by placing the Large-Scale Technology Projects under the management of collective bodies, of Engineering Research Associations, but we will see in the remainder of this chapter that this has only met with limited success.

Between 1972 and 1975, the ETL's Mark V MHD prototype was tested using a race-track shaped magnet with a stored energy of 60 million joules, the largest in the world at the time. Although the system generated 500 kW it consumed 24 MW of thermal energy in the combustor: the energy flow was still highly negative. Experiments at ETL continued between 1976 and 1983 bringing the total budget of the MHD activity to 11.4 billion yen.

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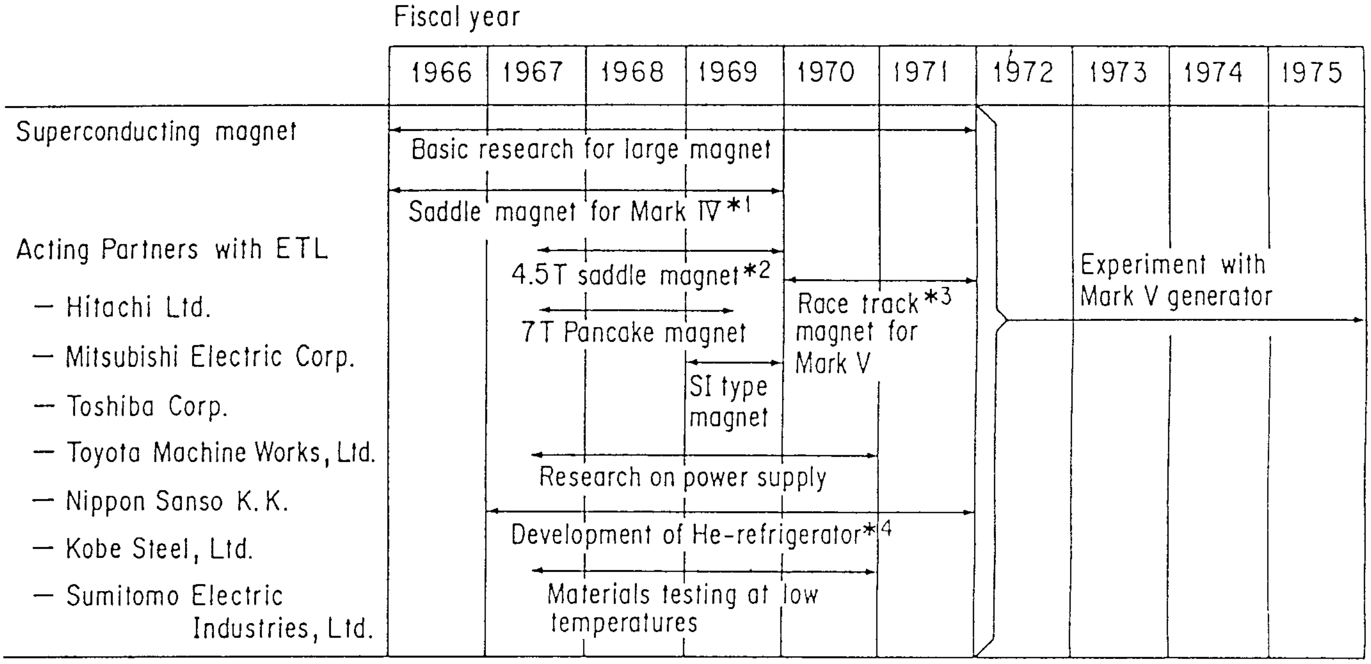
[11] Y. Aiyama, "Research on superconducting magnet system for MHD project in Japan," Fifth Cryogenic Engineering Conference, Surrey, England: IPC Science and Technology Press, 1974.



*1) $E_S$ = 0.35 MJ, W = 1.1 ton ; *2) $E_S$ = 4.5 MJ, W = 7.6 ton ; *3) $E_S$ = 60 MJ, W = 48 ton ; *4) LHe 250 ℓ/hr.

Figure 2. Distribution and Time Schedule of R&D Contracts in the MHD Program

More importantly for the world of superconductivity in Japan, the project allowed manufacturers to catch up to the international state-of-the-art in high field magnets. For superconducting magnet makers, this was the only significant market at the time. The program had successfully nurtured firms which would, to today, continue to dominate the superconducting magnet industry in Japan. It also nurtured their suppliers, as Hitachi Cable's first superconducting wires, for example, developed out of work for this project and took shape in the 4.5 T magnet. In the words of Dr. Aiyama, "It is no exaggeration to say that almost all groups now (in 1991) active in large-scale superconductor applications originated from and grew up with this project."[12]

The program also successfully encouraged other, non-participating firms to invest in the technology. Fuji Electric and Fujikura both indicated that they became involved in superconductivity as a result of the MHD project and Toshiba invested heavily in its own development of a high field magnet. Hitachi and Kobe Steel began in-house activity in

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[12] K. Oshima and Y. Aiyama,, op.cit., p.19.

helium liquifaction machines, which filled a gap left by Toyoda Machine when the firm discontinued its development after the project's completion.

With magnet development progressing successfully through the MHD program, individuals in the field began calling for a more broad based promotion of the technology's use. In 1970, Dr. Fusao Mori noted that the effort in Japan had focussed too exclusively on MHD as an application. He pointed out that there were many other applications receiving little attention such as accelerators, fusion energy, and electricity generation, and that only through a more broad based strategy could Japan could realize the hope of surpassing other countries in this field.[13] His essay was prescient of developments to come.

### - *Gradual Growth of Helium Liquifaction Technology in Japan*

The increased domestic capability in cryogenic technologies led to the gradual displacement of foreign technologies with those that were domestically developed. For example, over the 1960's the domestic cryogenics industry developed a competitive capability and gradually increased its market share. Mitsubishi eventually sold 29 of its units with sizes ranging from 1 to 20 liters/hour between 1963 and 1970. However as activity in superconductivity picked up through the 1960's, larger machines were desired and were developed by manufacturers such as Hitachi, Nippon Sanso, Daido Sanso and Teisan. Richard Brandt of the Office of Naval Research noted that between 1963 and 1967, domestically produced liquifiers gradually displaced imports in the Japanese market, and after 1967 the market was principally composed of domestic units.[14]

By 1970, it was estimated that 90 groups had active superconductivity programs in Japan, with about half of these being in universities and half in the private sector and government laboratories. Approximately 49 of these groups had their own helium refrigerators.[15]

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[13] Fusao Mori, "Chodendo Gijutsu to Ogata Purojekuto," Teion Kogaku, Vol.5, No.2, 1970, p.1.

[14] Richard Brandt, Superconducting Technology in Japan, ONR-28, Arlington,VA: Office of Naval Research, June 1971, p. 1.

[15] Richard Brandt, op.cit., p. 2; and K. Oshima and Y. Aiyama, op.cit. p.14.

- *Linear Motor Car*

At about the same time that the MHD project was getting underway, Japan as a nation was celebrating its first post-war opportunity to return to the global spotlight by hosting the 1964 Olympic games. It had been twenty years since the destruction of the war and the nation wanted to show that it had rebuilt itself and was ready to rejoin the circle of advanced nations. Externally Japan was making overtures to the international community to promote its revived status, with, for example, the government giving up its special trade status and its currency controls to join the Organization for Economic Cooperation and Development (OECD). Internally, the government was making major investments in infrastructure, upgrading general facilities and its services. An important symbol of the nation's advance at this time was embodied in the *Shinkansen,* or bullet train, which opened just in time for the start of the Olympics.

With the bullet train realized as the cumulation of a decade of development, engineers at the Japan National Railway (JNR) were faced with the question of what to do next. In 1962, as the bullet train project was nearing completion, a small group of engineers gathered to investigate alternative technologies for future vehicular propulsion. One such alternative was a magnetically based, linear motor propulsion system. Although the early experiments were conducted on a very small scale with conventional magnets, it was realized that conventional magnets would not provide the force needed to transport a car full of passengers or freight at high speeds, and by the late 1960's, the decision was made to continue with the prototype development of a superconducting linear motor car.

This project also involved a consortia of organizations in the private sector, sometimes conducting work in direct contract with the National Railway, and sometimes cooperatively with other firms. Three firms were selected as the principal developers of the needed superconducting magnets - Toshiba, Hitachi, and Mitsubishi Electric - the same magnet developers for the MHD project; and three firms were selected as the principal developers of the wires and cables - Furukawa, Hitachi Cable, and Sumitomo Electric.

Work on a prototype superconducting linear motor car began in 1970 with a goal of demonstrating the technology in two years so that it could be included as part of the celebration for the 100th Anniversary of Japan National Railway in 1972. In March of 1972 successful tests were conducted with a 2.0 ton test vehicle, the LSM-200, which reached a speed of 50 km/hr on the 220 m test track set up in the JNR Research facility.

Engineers were excited over the success of this technology but were still a step away from a public demonstration as the LSM-200 was just a steel block on wheels, looking more like a steel lunch box than a harbinger of an advanced form of transportation.

With the linear propulsion system proven, engineers converted the lunch box into a sleek-looking 4-seat cab which floated over a central rail track. In October of 1972, the ML-100 was unveiled at a public ceremony marking JNR's 100th anniversary (ML stands for magnetic levitation and the 100 signified the 100th Anniversary of the railway.)

The evolution of the technology will be described in more detail in one of the following section analyzing the politics and organization of the program. But briefly, the project continued to evolve and was highlighted by the performance of the ML-500 prototype, which on December 21, 1979 reached a world record speed of 517 km/hr at the Miyazaki test site. The linear motor car program continues today with the testing of a 44 passenger prototype, the MLU-002, and the construction of a 50 km test track in Yamanashi Prefecture. Optimistic plans look for the initiation of commercial service between Tokyo and Osaka by the year 2000.

### - *Superconducting Electricity Generator*

The next major project that arose which involved the use of superconducting elements was an electricity generation project with superconducting materials used in the generator. In 1974 MITI provided a conditional loan (*hojokin* grant) to 2 firms, Mitsubishi Electric and Fuji Electric, to develop a 6 MVA prototype generator. In 1977, this was followed by a five-year program funded through a similar conditional loan to develop a 30 MVA generator, with the same two firms as the principal developers. These projects marked the only occasions to date in superconductivity in which competing systems manufacturers physically cooperated in the hardware development of a superconducting technology.

On these two electricity generator projects, these two firms managed to operationally cooperate in the construction of common prototypes. In the 6 MVA project, Mitsubishi Electric contributed the superconducting coil and the stator, and Fuji Electric made the non-superconducting rotor. The budget was split roughly evenly between the two firms, with MITI providing 120 million yen and the companies contributing 410 million yen, bringing the total system budget to 530 million yen.

In the 30 MVA project, Mitsubishi Electric developed the superconducting coil, the stator and half of the stator coils, and the helium refrigeration equipment. Fuji Electric again made the non-superconducting rotor and half of the stator coils. For this project, roughly all of the contributions doubled with MITI providing 250 million yen, and the firms 820 million, bringing the project total to 1.07 billion yen. The budgets were again split roughly in half between the two firms.

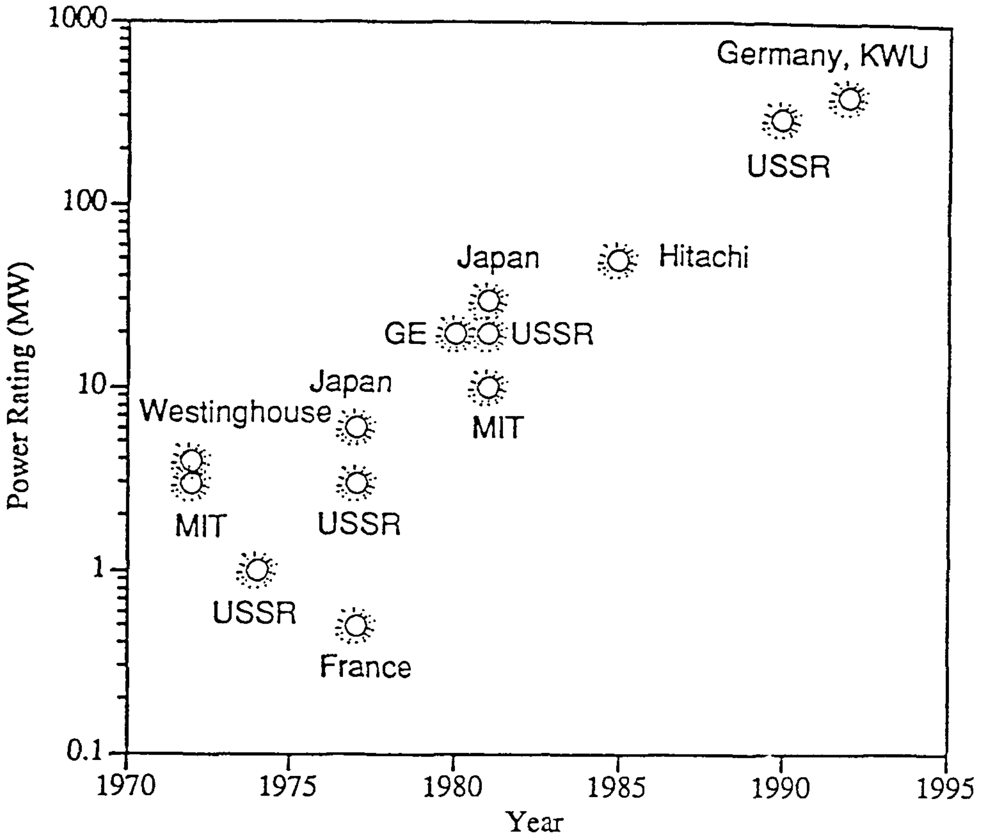

Figure 3. Progress of Superconductor Generator Development in Various Countries

In both projects the units were assembled at the Mitsubishi Electric plant. Participants commented that it is was an unusual instance of competitors actually cooperating without significant conflict. Participants noted that a major reason for the lack of conflict was the immature state of the technology in the world, particularly in Japan. Before the project, Fuji Electric had experimented with the development of a 30 KVA model, Toshiba was developing a single pole 3 MW model, and Hitachi had just begun with basic studies of the technology. There were no leaders in the field in the country, application was clearly far in the future, and sales would be to a limited, government regulated market. Mitsubishi Electric and Fuji Electric were selected because these two firms were willing to bear the greater than 75% cost sharing requested by the government.

These projects kept Japan in pace with international developments and eventually led to the creation of the SUPER GM project. Initiated in 1988, the Super GM Project has the goals of developing 70 MVA prototype fast reaction and slow reaction generators in preparation for scale up to a 200 MVA prototype whose development would begin in 1996. The major developers of the superconducting components were again Mitsubishi, Toshiba, and Hitachi, with most of the major cable manufacturers also involved.

The general progress of superconducting generator development worldwide is sketched in Figure 3.

- *Superconducting Electromagnetic Propulsion Ship*

Another project to begin significant development in the early-1970's is the electromagnetic propulsion (EMP) ship. Unlike conventional propellor propulsion, this design takes advantage of a stationary electromagnetic thrust system. In this system, a current is induced in sea water via electrodes, with the sea water then passing through a powerful magnet. The interaction of the current and the magnetic field results in momentum being imparted to the water, which appears as thrust to propel the ship. One major advantage of this design is an increase in speed. Whereas propellor driven ships have a speed limit of around 40 knots, the EMP ship has a top theoretical speed of 100 knots.

As was the case with each of the previous technologies discussed here, the idea for this propulsion design was born abroad. The first patent was filed in the United States by W.A. Rice in 1961. By 1966, S. Way at Westinghouse demonstrated a small model ship which used normal conducting magnets for practical applications. However, their calculations revealed that extremely high magnetic fields would be needed, and these could only be delivered by superconducting magnets.

Then in the early-1970's, a research team combining university and industrial laboratories initiated experiments in Japan. Kawasaki Heavy Industries, Osaka University and Kobe University began the first prototype activity in Japan. This work was largely funded by the Ministry of Education's Special Project Research Grants.

Their work led in 1976 to the first demonstration of a superconducting EMP ship, the SMED-1. This test prototype used a small superconducting coil and was principally constructed as a proof of concept model. The prototype was improved to a more true to life ship design, and in August 1979 the ST-500 was test run in the open water. The ST-500 was 3.6 meters long, weighed 700 kg, used a 2.0 telsa superconducting magnet made by Kawasaki Heavy Industries, and had a speed of 1.75 knots.

Development in Japan of the EMP ship accelerated in June of 1985 when the Japan Foundation for Shipbuilding Advancement initiated a more ambitious prototype development program. Under their Superconducting Electromagnetic Propulsion Ship Study Committee and with financing from the Japan Shipbuilding Industry Foundation, they began development of the Yamato I experimental ship. The Yamato I is designed to carry 10 passengers and is 30 meters long, weight 150 tons, and will travel at 8 knots using two superconducting magnets with a strength of 4 telsa. The superconducting coils were provided by Toshiba and Mitsubishi Heavy Industries, with Mitsubishi Heavy Industries also in charge of overall ship construction. The overall cost of constructing the ship is estimated at 3 billion yen,[16] and sea testing of the prototype is scheduled to begin in early 1992.

### - *High Energy Particle Accelerator*

The largest of these was the national project involving the use of superconducting materials for the research of particle physics at the National Laboratory for High-Energy Physics (*Ko-Enerugi Butsurigaku Kenkyujo*, KEK) in Tsukuba. Here superconducting magnets provide both the high fields necessary for acceleration, as well as for particle detection. A 12 GeV synchrotron was completed in 1976 with the delivery of the first superconducting magnet, a Muon Channel Magnet manufactured by Furukawa Electric in 1980. Between 1981 and 1985, four other superconducting magnets were added, one manufactured by Mitsubishi Electric, one by Hitachi, and the other two by Furukawa Electric, and in 1986 the TRISTAN facility, an electron-positron colliding accelerator, was completed. By 1991 the facility had incorporated 17 superconducting magnets and a superconducting cavity for a range of physics experiments. Mitsubishi Electric and Toshiba each supplied a total of four magnets, Hitachi three, Furukawa Electric three, Ishikawajima-Harima one, and KEK itself manufactured two. A list of the magnets is provided in Appendix A.

### - *Nuclear Fusion*

The largest potential market for superconducting materials in general may be its use in nuclear fusion, if the process is ever realized. Mainstream research in this area involves the fusion of deutrium atoms or deutrium and tritium atoms at extremely high temperatures. In this process the atoms are heated to extremely high temperatures until the electrons are stripped off, creating a plasma of free electrons and atomic nuclei. Under normal conditions these nuclei would repel each other because of their common positive charge. However the high temperatures in the reactor excite these nuclei, impelling them to smash into each other at high speeds and fusing into one nuclei. This fusion releases a large amount of kinetic energy in the neutrons created, and this energy can be captured and

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[16] "Sekai hatsu no Chodendo Sen," Yomiuri Shimbun, June 12, 1991.

converted into heat and electricity. To achieve the fusion reaction, however, temperatures on the order of a hundred of million degrees Kelvin are required.

The temperatures are so high that the process cannot be contained by solid surfaces, as these surfaces would melt. To contain the fusion reaction, then, scientists have turned to the use of high magnetic fields.

Because fields greater than 10 telsa are required, normal magnets are inadequate for fusion containment. Instead, superconducting magnets must be used to achieve the conditions needed. Even with the field intensities made available through superconducting magnets, the overall magnetic system is anticipated to be very large, greater than 10,000 tons, which is one half the total design weight of Japan's planned Fusion Experimental Reactor (FER). With a conventional magnet, joule heating in the magnet would lead to a system requiring 2,000 MW of power, which would be five times the thermal output of the reactor. With a superconducting system, the electric power needed for the helium refrigeration system would be around 30 MW. [17]

Plans for a nuclear fusion program in Japan began to accelerate soon after the oil shock of the early 1970's. An Advisory Committee on Nuclear Fusion had been established in 1958 within the Atomic Power Commission, and in 1968 a Basic Program for Research and Development of Nuclear Fusion was issued by the then renamed Atomic Energy Commission. However, it was not until the mid-1980's that the activity rose to the priority of a significant national project.

In the autumn of 1974 the International Energy Agency (IEA) was established in the Organization for Economic Cooperation and Development (OECD), and within the IEA a Fusion Power Coordinating Committee was created. The mandate of the committee was to come up with a proposal for interaction cooperation in R&D. During the same period, a Fusion Council was established in the Japan Atomic Energy Commission and discussions were initiated over a fusion R&D strategy.[18] Then in 1975, the Nuclear Power Advisory Committee to the Japan Atomic Energy Research Institute (JAERI) recommended the initiation of a national effort to pursue fusion as an energy source for the nation's future.

In March of 1975 the IEA came up with R&D proposals which included a Large Coil Task (LCT), a program intended to test a toroidal arrangement of large superconducting coils. Japan joined the United States, Euratom, and Switzerland and the

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[17] S. Shimamoto, "Development of Superconducting Magnet for Fusion Power," Presented at First International Conference on High Temperature Superconductivity, August 28-31, 1988, Nagoya, Japan, pp. 43-49.

[18] K. Oshima and Y. Aiyama,, op.cit., p.22-24.

LCT program was started in 1977. Prof. Yasukochi, Professor at Nihon University and Chairman of the Superconducting Materials Subcommittee in the Fusion Council, took the lead in planning Japan's participation, with the administration formally shifting to a new Superconducting Materials Section in the Fusion Division of the Japan Atomic Energy Research Institute. Dr. S. Shimamoto was its first head.

With JAERI in charge of the toroidal field system and Hitachi, Ltd. responsible for manufacturing the NbSn3 magnet, the LCT coil was delivered to the test site at the Oak Ridge National Laboratory in the Untied States in November 1982. It was tested along with five magnets from other countries and the coil produced a 12 telsa field at 6.5 kA.

While the toroidal coil system was being developed by JAERI, ETL took the initial lead in poloidal coil development. A 4 MJ coil was developed in the early 1980's, after which time the technology was transferred to the JAERI Demonstration Poloidal Coil Program. The coil was manufactured by Mitsubishi Electric and was designed to have a stored energy of 40 MJ and a pulsed field rate of 7 telsa/second.

In 1986, the Triam fusion reactor, Japan's Tokamak machine, began operation at Kyushu University. The reactor is designed with a stored energy of 76 MJ and a maximum field of 11 telsa. The Toroidal magnet is made of NbSn3, manufactured by Hitachi, and has a current capacity of 6,000 A. In early tests it generated a plasma current of 0.5 MA.

In this period the Ministry of Education also joined in promoting the field, initiating a 10-year Fusion Research Program through the Special Research Project Fund in 1980. Over the 10 year term, 7.145 billion yen in research grants were distributed through this program.[19]

### - *Superconductive Quantum Electronics - Ministry of Education*

In 1979, the first government project directed toward electronics applications of superconductivity was initiated by the Ministry of Education. This was a special research program on "Superconductive Quantum Electronics" and was funded at 681 million yen over three years. Each year there were an average of 25 themes with each theme involving about five researchers, and with the majority of the research focussing on the fabrication of Josephson junctions. The researchers experimented with a variety of lead and niobium

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[19] "Kakuyogo Tokubetsu Sogo Sokatsu han Jigyo Hokoku, Kagaku Kenkyu Hi - Saitaku Kadai, Tokyo: Monbusho, 1980-1989.

alloys and junction types, such as tunnel junctions and tunnel and coplanar bridge junctions.

One of the more important effects of this program was that it provided a base of domestic experience with this technology, and a source of data from which subsequent projects could draw. Ko Hara, project leader, noted that "As a result of the special research project, the laboratories of NTT, MITI and industry have now begun their own research programs. We have a good expansion of the research work since the project began."[20]

### - *MITI Supercomputer Project - Josephson Junctions*

MITI's first program addressing superconducting electronic devices began to take form in 1980 as it was investigating new options to increase the power of large-scale computers. By the mid-1970's IBM had developed a rather large-scale effort to develop Josephson junction technology as a means of attaining faster switching speeds in their computers. By using Josephson junctions rather than semiconductors, the switching speed can theoretically be reduced by 100-fold, thereby vastly improving the computing power of a computer.

The Japanese government and the major computer firms had spent the previous two decades using IBM as a target and inspiration for their policies,[21] and this technology was another in the line. In 1981, MITI initiated a 10 year long Supercomputer Project under its Large-Scale R&D Project system to help Japanese firms "catch up" with IBM. As part of this project, the researchers investigated three types of switching devices, of which the Josephson junction was one. The work on this Josephson junction technology will be explored in more detail later.

### - *Novel Superconducting Materials - Ministry of Education*

In 1981, Prof. K. Yasukochi convinced the Ministry of Education to sponsor two workshops to discuss the possibility of a broader program to search for superconductivity in new materials. Prof. Yasukochi had an interest in the large number of non-reproducible reports of higher temperature superconductivity and felt that a systematic program to investigate alternative materials would be very useful in sorting out their promise. The first

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[20] Ko Hara, Proceedings of Symposium on Superconductive Quantum Electronics, Conference held at the International House of Japan, August 30-31, 1982, Tokyo: Ministry of Education.

[21] Marie Anchordoguy, The State and The Market: Industrial Policy Towards Japan's Computer Industry, Ph.D. Dissertation, 1986.

workshop was titled Novel Types of Superconductivity and was followed in 1982 by a second workshop titled New Superconducting Materials. During the first workshop research on superconductivity at home and abroad was reviewed to clarify the state of research in this field. Researchers concluded that in the cases of virtually all novel materials, such as ternary compounds, inorganics, organics, and amorphous films, there were significant shortcomings in the theories of material behavior. Thus any further work in the field needed to couple the theoretical and experimental work. At the second workshop, researchers presented plans to expand research in this field, with a formal proposal being submitted to the MOE in 1983.[22]

In 1984 the MOE launched a three year program to support the search for new superconducting materials. This was the first major government program which had as one of its explicit goals the discovery of materials that superconduct at high temperatures, with the eventual hope of finding a material that superconducts at room temperature. It was under funding from this program that Prof. Tanaka conducted his experiments which confirmed the IBM-Zurich discovery.

At this point the technology was gaining greater recognition as one that could be realistically applied to a variety of systems and devices, with the markets for superconducting cables and wires continuing to grow.

### - *First Superconducting Device for a Major Commercial Market, Magnetic Resonance Imaging*

In 1984, the first Japanese firm entered the Magnetic Resonance Imaging (MRI) market, a commercial technology whose performance can be substantially upgraded with the use of a superconducting magnet. In this year, Furukawa Electric teamed with Oxford Technologies and began manufacturing and marketing MRI devices in Japan. Soon after, several other Japanese firms introduced their own versions, and in the late-1980's sales grew rapidly.

MRI works by taking advantage of large field magnets to produce images of tissues in the human body.[23] In this technique, a magnetic field is first applied to the

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[22] Sakao Nakajima, "Historical Survey," Superconducting Materials, JJAP Series 1, S. Nakajima and H. Fukuyama eds., Tokyo: Japanese Journal of Applied Physics, 1988, pp. iii.-v.

[23] This description was aided by very clear and more detailed descriptions provided in publications including the following: Randy Simon and Andrew Smith, Superconductors, New York: Plenum Press, 1988 , pp. 203-210; and Chirt T. Moonen, et.al., Functional Magnetic Resonance Imaging in Medicine and Physiology," Science, Vol. 250, October 5, 1990, p.p. 53-

region of the body to be imaged. This causes atoms in the body, most notably the hydrogen atoms, to align with the field. Then a brief burst of energy is applied to scramble the atomic alignments. When the pulse of energy ceases, the atoms return to alignment with the magnetic field, and when this happens, a small amount of energy is released. The frequency of the energy depends on the type of atom emitting the energy. In addition, the speed at which these molecules return to their alignments is highly influenced by the local chemical environment and the mobility of the molecules. Thus by measuring the characteristics of atomic realignment the composition of the tissue can be imaged.

MRI complements the use of X-Ray analysis and provides a more detailed map of tissue than available with ultrasound. X-Rays are still the preferred technique for examination of fractures and skeletal abnormalities, but tissue is largely transparent to this technique. And unlike MRI, X-Rays tend to damage cells in the body when applied. Ultrasound is a tissue imaging technique like MRI and is also noninvasive, but does not offer spatial resolution that is as high. Ultrasound, for example, has difficulty in imaging deep and small vessels, particularly those near the bone.

The application of MRI requires that relatively high magnetic fields be available to obtain the desired atomic movements described above. These high field magnets do not have to be superconducting, and in fact, the first commercial MRI units used conventional magnets. However, the magnetic field must not only be strong and uniform, but must be stable, with variations of less than one part in a million for periods that can be longer than an hour. The persistent currents in superconducting magnets provide such an ability to keep fields constant. In addition, superconducting magnets are more compact and lightweight than conventional magnets, which makes them accessible and easier to install in existing hospital spaces. Current field strengths used in MRI devices range from 0.5 telsa to 2.0 telsa, with Japanese manufacturers particularly strong in the manufacturer of the smaller machines.

An important point in the development of this technology is that in this market, which would soon become the largest market for an application of superconductivity, the government had no direct promotional policies: this market was not aided by government foresight. However, the manufacturers of the superconducting magnets and the leading MRI manufacturers are the same firms that have been raised on past superconductivity programs. By maintaining a set of competitive firms in this generic technology, the government indirectly aided their timely and successful entry into this field.

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61; and Juri Matisoo, "The Superconducting Computer," Scientific American, May 1980, pp.38-53.

### - *Superconducting Magnetic Energy Storage*

In the early-1980's, again spurred by activity overseas, utilities and firms began to take a more serious interest in the use of superconductors for energy storage. Superconducting Magnet Energy Storage (SMES), provides a very efficient alternative to the storage of energy which is particularly attractive to power utilities. During the course of the day, the demand for electricity can vary greatly, being high on a mid-summer afternoon, for example, when air conditioning use is high, and low in the middle of the night, when most of the country is asleep. To accommodate these changes, plants must be operated at less than capacity or must employ supplementary power equipment, which is less efficient than the primary generation equipment. Another option is to run the plants at full capacity around the clock, and to store the energy when the demand is low so that it can be used later when demand peaks, a process known as "peak leveling."

Pumped water storage is commonly used for such a purpose. In this scheme where water is pumped from a lower reservoir to an elevated reservoir during periods of low electricity demand and released to run back down through hydro turbines when demand is high. However, whereas the efficiency of a pumped hydro system is typically on the order of 65-75%, the efficiency of a SMES system can be higher than 90%.

In 1986, 35 firms and utilities joined to form the "Chodendo Enerugi Chozo Kenkyukai," (Research Association of Superconducting Magnetic Energy Storage (RASMES)). The purpose of the Association was to diffuse information about the technology, lobby for support of this technology from the government, and to propose a strategy for the national development of the technology.

The initial members of the association included six utility organizations, twelve manufacturers, eight construction firms, and four consulting companies. Studies that have been conducted by the association have included the planning of a 50 MJ test plant, a 20 MWh prototype plant, and a 5 GWh commercial plant with application of SMES to the power system.

In an attempt to prod the government into action, the association presented a 10-year SMES development plan in June of 1989 which called for the prototype development of complete 100-1,000 kW and 1,000-10,000 kW SMES systems. The budget proposed was 40-50 billion yen.[24]

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[24] "Denryoku Chozosochi 10 nen de Jitsuyoka," Asahi Shimbun, June 22, 1989, p.1.

In the late-1980's, firms and utilities began to cooperatively invest in hardware to begin small scale prototype testing to demonstrate the feasibility of the technology. In 1988, Chubu Electric Utility joined with Hitachi to develop a 1 MJ SMES constructed with a pulsed superconducting magnet. In 1991, the Electric Power Development Company joined Toshiba to develop a 16 kJ device, and also in 1991 Mitsubishi Electric in cooperation with Kansai Electric Power began experiments with a 10 kJ prototype.[25]

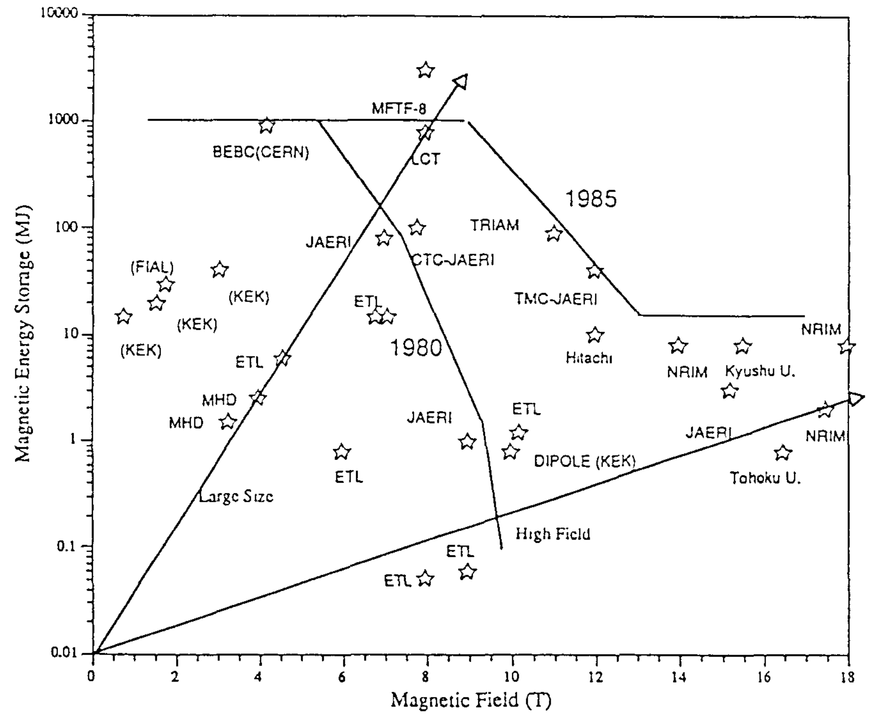

Figure 4. Progress of Superconducting Magnetic Field Strength

(Adapted from Shimpei Matsuda, et.al., "Hitachi Seisakusho no Chodendo Gijutsu no Tenbo," Hitachi Hyoron, Vol. 71, July 1989, p.4)

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[25] Hideki Fujita, "Power System Control Experiment Using 1 MJ SMES, Proceedings of the 2nd International Symposium on Superconductivity (ISS '89), November 14-17, 1989, pp. 1041-1046; "Denhatsu-Toshiba ga Shikin - Chodendo Enerugi Chozosochi," Nikkei Sangyo Shimbun, February 4, 1991, p. 17; and "Chodendo Chikuden wo Jisha Jikken," Nikkei Sangyo Shimbun, June 12, 1991, p.19.

After a subsequent year of negotiation, a core set of twenty firms were formed into a Research Association with commitment extracted from MITI for a 10-year SMES research and development project under the Moonlight Program.[26] Again, the principal suppliers of superconducting technology will be Hitachi, Toshiba, Hitachi Cable, Furukawa, and Sumitomo Electric. The goal of the project is to develop a 100 kW-hr prototype. The overall project funding is estimated to be 25 billion yen.

### - *Increasing Superconducting Magnet Capabilities*

Through the combination of technology promotion programs and technology purchasing - through a combination of technology push and demand pull - the performance of large superconducting magnets in Japan steadily increased over the past two decades. Through continuous support of the same set of cable and wire manufacturers and same set of systems developers, and through continuing innovation in these firms, the industry in Japan is now producing arguably the best technology in the world. The progress of magnetic strength and energy level over time is summarized in Figure 4.

The levels of performance can be expected to continue to increase as demanding uses such as Nuclear Fusion and Magnetic Energy Storage continue to advance. Nuclear Fusion, for example is in the midst of a major development and testing program. For the next stage of fusion experiments, JAERI is in the middle of its JT-60 program. This Table involves developing a 12 T large diameter (10-15m) DC toroidal coil, a 7 T large diameter (5-20m) pulse poloidal coil, and a 12-13 T large diameter (3-4m) pulse solonoid coil.[27] This project will also bring advances in the accompanying cryogenic technology as 300 l/hr, 1,200 W helium refrigerator developed in 1981 will have to be scaled up to a 3,000 l/hr, 10 kw unit for experiments planned in the early-1990's, and eventually to a 9,000 l/hr, 30 kW unit after 1996 for the Fusion Experimental Reactor.[28]

### - *Firm Concentration, but Little Cooperation*

In our discussion of the history of superconductivity, we noted that a number of R&D programs have been supported by the government which involved the development of LTS. Table 3 summarized the principal participants in government programs involving

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[26] The response from MITI is that the project is planned in two distinct phases, with only the first five year phase receiving MITI commitment at the outset.

[27] *Genshiryoku Kenkyujo, "Kakuyugo Kenkyu Kaihatsu no Genjo,"* June 1990.

[28] *Genshiryoku Kenkyujo, "Kakuyugo Kenkyu Kaihatsu no Genjo 1989"*, p. 90.

Table 3. Primary Firms in Government Programs That Involved the Development or Use of Superconducting Materials

| Project | Firms |
|---|---|
| Magnetohydrodynamic Generator | Hitachi Ltd., Mitsubishi Electric |
| Linear Motor Car | Hitachi Ltd., Mitsubishi Electric, Toshiba |
| 6 MVA Generator | Fuji Electric, Mitsubishi Electric |
| 30 MVA Generator | Fuji Electric, Mitsubishi Electric |
| Supercomputer - Josephson Junctions | Hitachi Ltd., Fujitsu, NEC |
| Electromagnetic Propulsion Ship | Toshiba, Mitsubishi Heavy Ind. |
| Super GM (70 MVA Generators) | Hitachi Ltd., Mitsubishi Electric Toshiba |
| Superconducting Magnetic Energy Storage | Many |

the development of LTS which were initiated before 1986.

In all cases, coordination primarily took the form of dividing the responsibilities for tasks between the principal performers. This brief review of history show that as a general rule cooperation did not involve work at a common facility nor did it involve dependencies between firms with competitive market interests. Competitors conducted their R&D separately. In the case studies that follow in later sections of this report, I will examine evidence of collaboration between competitors in more detail.

## Summary

This discussion of the history of the LTS industry in Japan, has attempted to provide some sense of the range of projects and policies that have contributing to building up the industry of today. We do not see an overarching central policy to develop this material, but a number of different projects sponsored by a number of different organizations to exploit the advantages of this material's performance for specific uses.

We see that the same principal organizations are frequently involved in supplying the superconducting systems across the various technologies, and that there are usually several firms involved, not just one. It would be a mistake however, to conclude that continued participation is guaranteed by the government. Fuji Electric was one of the first of the Japanese firms to work with MITI on early prototypes of the superconducting generator in the early -1970's, but it gradually lost its footing as competing firms invested more in this technology and was most recently excluded from the Super GM Program.

Although participation in the government program provides some barrier to entry for the participants, this is not necessarily so for systems developers in new markets. The MRI market has developed with almost no direct aid from the government. Although led by firms traditionally strong in superconductivity such as Hitachi and Toshiba, newcomers such as Shimadzu are finding this to be a profitable market, and old timers such as Fuji Electric are finding that in spite of their experience, a short lag in trying to enter this market has made penetration very difficult.

By the end of 1986, then, a variety of publicly supported projects had the combined effects of establishing a small but internationally competitive superconductivity industry composed of the nation's major cable and wire makers and systems manufacturers. Rather than primarily through a technology push of the material's development, however, the industry also grew through procurements in government projects. As Richard Brandt noted in his report to the Office of Naval Research in 1971, for example, the MHD project provided a market that enabled participation in superconductivity by a number of firms, which would not have been possible with the otherwise limited market.[29] The pull of government procurement has had a continuing role in the development of superconductivity through the 1970's and 1980's and has, as we will see, been boosted into the 1990's by the development of HTS.

Finally, as background to the national projects of the 1980's and 1990's, this history shows that collaboration in research and development was not the norm. With the principal actors small in number, the risk high, and the technologies typically at a primitive state of development, we might have expected to see more collaboration occurring. Some vertical relationships developed, but the firms from the same sectors preferred to act independently when they could, competing more than cooperating.

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[29] Richard Brandt, op.cit., p.2.

## Linear Motor Car

In this section I will review the linear motor car program in more detail as it provides an illustration of both the use of collaboration and competition to promote technology development and the interplay with politics which has proven essential to the continued support of the project. In this project, technological cooperation will be seen to be limited, grouped, and internally rational - themes which will continually reappear in the later analysis of projects in 1980's and 1990's.

As introduced in the historical review, the research program into this technology began in 1962 as the *Shinkansen* (bullet train) program was nearing commercial operation and as engineers in the JR Research Laboratory began exploring alternatives for the next evolution in ground transportation technology. The Shinkansen was designed to be able to travel at speeds near 200 km/hr which at the time was considered a phenomenal leap over the 50-60 km/hr speeds of conventional trains. However, designing a train to travel much faster posed problems for designers. Higher speed brings higher levels of friction and wear to the wheels as well as high levels of noise and vibration. Higher speeds also pose problems in transferring current to the train to propel the vehicle. The general sense of the engineers at the laboratory was a speed of just over 300 km/hr would be the maximum achievable with a conventional train design.[30,31]

A magnetic propulsion system had the advantages of eliminating these restrictions on speed as the vehicle would float above the guideway and the energy could be provided from the track. Thus in 1962 engineering at the JR Research Laboratory engineers began bench level experiments with a linear motor system. The technology itself had been known since the discovery of the rotary motor but had largely remained unexploited. In 1945 a linear propulsion system had been proposed for the launching of rockets and missles. But it was not until 1966 that two Americans at the Brookhaven National Laboratory, J.R. Paul and G.R. Danby, published an overview of a magnetically levitated train using superconducting magnets. This added momentum to arguments for the development of this technology in Japan.

Through the 1960's, experiments on the linear motor design progressed very slowly. The bench scale device was scaled up to a backyard scale test facility, but work was executed at a relatively low level of priority.

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[30] Tetsudo Sogo Gijutsu Kenkyuujo, Rinia Moutaakaa Magurebu, Tokyo: Seibunsha, 1988.

[31] The French TGV conventional high speed train system operates at 270 km/hr on dedicated track but has plans in place to increase speeds to 350 km/hr by the end of the century. They also consider an operating speed of 400 km/hr to be possible. (Barry Jones, "The New Generation of High-Speed Trains," International Herald Tribune, October 31, 1990.)

Then came the World's Fair in Osaka in 1968, with millions of national and international guests making the voyage down from Tokyo to view the international exposition. The large volume of passengers services not only resulted in an increased awareness generally of the convenience of this high speed service, but overloaded the *Shinkansen* system, increasing awareness that capacity was finite. By 1969 voices were calling again for an expanded and faster form of service to eventually succeed the *Shinkansen*. The next goal was travel between Tokyo and Osaka in one hour, but this would require maximum speeds of around 500-550 km/hr.

## The Technical Advance

At the JR Research Laboratory, Yoshiyasu Kyotani, head engineer in the survey group, led a study team which concluded that to provide this service the linear motor car would be the best option, and that the performance desired could only be provided through the use of superconductivity. Conventional magnets, for example, could only provide enough field strength to lift the car 1 cm above the guideway. In this land of frequent earthquakes, this would not provide enough clearance for safe operation should the tracks shift. Instead, a clearance of 10 cm was desired, and this could only be achieved by using superconducting magnets.[32,33]

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[32] The decision to employ superconducting magnets may have been the appropriate one given the scale of the transportation system and concerns about earthquakes, land movement and snow along the path of the linear motor car, but it also leaves space for the program's competitors to exploit markets for their alternatives in the interim. Japan's other linear motor car, the HSST, has been under development since 1974 by a consortium of companies known as the HSST Corporation. It was travelled the International Exposition Circuit over the past 5 years giving rides to thousands of curious fair goers. In addition, the Germany government has been supporting a consortium of firms known as "Magnetbahn Transrapid" for the development of a linear motor car known as the Transrapid, also since 1974. Both the HSST and the Transrapid are much closer to commercial application than JR's linear motor car. Both use conventional magnets, which limits the lift to 1 cm, in contrast to the 10 cm of the linear motor car, and consequently reduces the margin for error and the speed. However for short distances and stable terrains this may be more than adequate..

The HSST has achieved a speed of 307 km/hr and the Transrapid has reported a speed of 412 km/hr. (The top speed with passengers for the HSST is still 110 km/hr, whereas the 412 km/hr Transrapid test was with passengers.)

In Japan, HSST has achieved agreement to construct a 10 km track in Aichi Prefecture that would be designed for inner city use. Another potential application would be a route that would link Narita and Haneda International Airports near Tokyo with the City's center. HSST has had more success, however, outside of Japan. In 1989 it initiated negotiations with the city of Las Vegas, Nevada for a 7 km track connecting the city to its airport, and in July 1990, the HSST Corporation announced that it had obtained a contract to test the feasibility of a 21 km line which would connect Moscow with its Sheremetyevo International Airport, allowing the commute to be made in 15 minutes. ("Japan to Build a Magnetic Train for Moscow," International Herald Tribune, July 12, 1990; "Mosukuwa ni Nihon Sei Rinia," Tokyo Shimbun (yukan), July 11, 1990.) The project is scheduled to start in 1991 and to be ready for service by 1996 at a cost of 90 billion yen.

In 1970 the decision was made to proceed with a superconducting magnetic levitation transport system. While much of the device work and systems integration were performed by engineers at the JR laboratory, the components were contracted to private developers. For the magnetic guidance system, Hitachi, Mitsubishi Electric and Toshiba were selected. It was agreed that the lead on the superconducting magnet would alternate with each succeeding generation of the technology, but that all would contribute.

1972 marked the 100th Anniversary of the Japan National Railway, and as mentioned earlier, to highlight the celebration the organization wanted to be able to demonstrate a prototype of this new technology. The first successful prototype, the LSM-200, was successfully operated in March of that year but was intended more for laboratory proof of concept than for public display. LSM is an acronym for linear synchronous motor and 200 represents the 220 meter length of the test track. A picture of this prototype is shown in Figure 5. The LSM-200 was a 2 ton vehicle, which was levitated and propelled by the magnets mounted in the car and railway. Conventional magnets were lined up in the middle of the track and the superconducting magnets were placed on the bottom of the car. Guidance, however, was provided by wheels and not the magnets themselves. The vehicle reached a maximum speed of 40 km/hr.

Seven months later, in October of 1972, a much sleeker prototype was unveiled to the public on the laboratory grounds - in time to help mark the Anniversary. This vehicle, the ML-100, was designed to seat four passengers and ran over a central I-beam guideway, as is shown in Figure 6. This was a 3.5 ton vehicle that could reach a maximum speed of 50 km/hr. The use of a linear synchronous motor design was, however, considered too premature for this important a public exhibition, so a more proven linear induction system was used for propulsion. It was the only time a linear induction motor was used. In addition, a slide shoe was employed for guidance to better assure that the event did not

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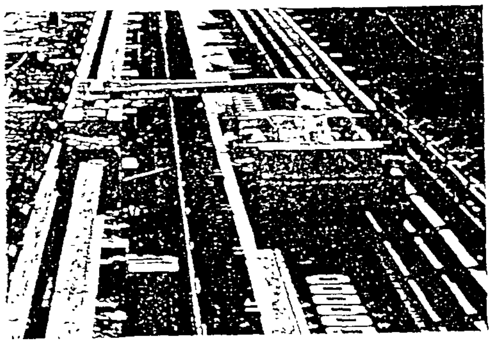
Within Germany, the Transrapid is scheduled to operate along the 150 km route between Hannover and Hamburg by the end of the 1990's. Outside of Germany, the organization announced an agreement with the City of Pittsburg in January 1990 to adopt Transrapid technology to connect the 28 km between its international airport and the city center. Although just in its initial feasibiltiy study phase, the project is estimated to come to $400 million when completed. ("Bei no Kosoku Rinia Dounyu Keikaku," Sankei Shimbun (yukan), January 25, 1990.)

The long-term competition with these alternative technologies is thus a battle that will await JR's linear motor car as they try to promote it in the next century.

[33] The use of superconductivity also means the use of a repulsive magnetic rather than an attractive magnetic design. Attractive systems are unstable unless the current in the magnet can be varied widely and rapidly, which is possible with normal magnets but not with superconductors. Without this control, the gap between the car and rail can continue to narrow until it closes. Superconductors, however, must operate with a constant current, and thus cannot be operated to maintain a constant gap in an attractive design. (Richard Thornton, "Why the U.S. Needs a Maglev System," Technology Review, April 1991, pp. 31-42.)



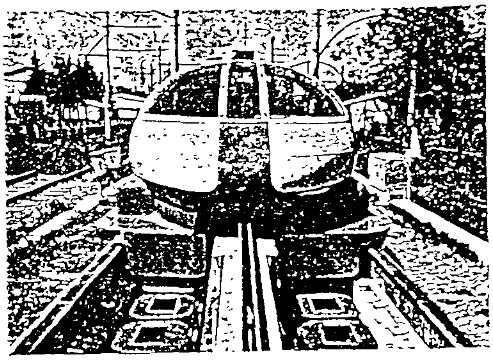


Figure 5. The LSM-200 Figure 6. The ML-100

(From Yoshihiro Kyotani, "Chodendo Jiki Fujo Ressha no Genjo to Korekara,"Teion Kogaku, Vol. 10, No. 3, 1975. pp. 81-82)

suffer from untimely collisions with the guideway. Although technically much different from the eventual operational LMC design, the exhibition gave public of the potential for superconducting transportation.

For actual operation, however, it was desired that guidance of the vehicle also be achieved in a non-contact fashion. This was achieved through a "null flux" magnetic circuit which had the additional advantage of avoiding losses from currents that could be induced in the ground coils from the motion of the vehicle - running resistance losses. With this guidance system, no magnetic field is induced and no loss occurs while the train is running in the middle of the track. When the vehicle deviates from the center, a current is induced in the coil which counteracts the shift and a correcting force is created which is proportional to the deviation. This guidance system was unveiled in 1975 with the demonstration of the ML-100A.

Until this time all of the testing had been conducted at the Tokyo, Kunitachi laboratory. However, further scaling up of the vehicle and higher speed testing required a longer test track, and in 1977 a 7 km test track was inaugurated at Miyazaki in Kyushu. The length of 7 km was calculated to be the minimum needed for safe operation of a vehicle up to a speed of 500 km/hr, which it was hoped, would be the eventual design speed of a commercial linear motor car. The track took the shape of an inverted-T, with the superconducting coils used for propulsion, levitation, and guidance, and the ground coils used for propulsion and guidance. For vehicle control, a variable-voltage, variable-frequency cyclotron converter was employed, and a regenerative braking system was used to capture energy that would otherwise be lost in bringing the train to a halt. It would be on this track that the test of the vehicle's potential speed were to be conducted.

With a basic design modelled on the ML-100A, the ML-500 was constructed to challenge the 500 km/hr goal targeted for the linear motor car. Through late-1977, 1978 and 1979, speeds were gradually increased beyond 100, 200, 300 km/hr to confirm the control and stability of the vehicle.[34] Finally, in December, the ML-500 achieved a speed of 517 km/hr which still stands as a world record for train prototypes. The JNR engineers had successfully demonstrated the feasibility of running a linear motor car at a speed of more than twice that of the Shinkansen.

As a result of the successful of the 517 km/hr demonstration, support for the linear motor project was high in the press, the public and among politicians. This was the peak of the project's national salience to this date, and since.

The next step was to demonstrate that the vehicle could operate safely with passengers. At this time, the shape of the guideway was revised from the inverted-T shape that had been used until then to a U-shape. As a result, the passenger section of the car would no longer have to ride entirely over the track but could to some degree be nestled within it, providing for a more stable ride and making the overall design more compact. The more streamlined the design, the less the aerodynamic drag, which is a significant energy loss at the high speeds at which the vehicle travels. The compactness of the design is also important in reducing tunneling costs for the eventual railway. It is estimated that 60-80% of the linear motor car's route between Tokyo and Osaka will involve travel through tunnels.[35]

Between 1980 and 1982 the U-shaped track was developed along with the MLU-001 (the addition of the U refers to the U-shaped design). In addition to testing the new design shape, the MLU-001 was also designed to test operation with multiple cars and to test the performance of a newly developed, compact and powerful 700 kA magnet. This

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[34] Tetsudo Sogo Gijutsu Kenkyujo, "Fujoshiki Tetsudo," Tokyo: Tetsudo Sogo Gijutsu Kenkyujo, circa 1978.

[35] Estimate based on conversations with representatives in Land Planning Agency and the Ministry of Transportation and "Eigyo Unten Mezashi Kensetsu GO!," Tokyo Shimbun (Yukan), November 28, 1990.

magnet had 55% greater magnetomotive force than its predecessor used in the ML-500, and allowed the single superconducting coil to provide all three functions of propulsion, levitation, and guidance. It was initially estimated that this design would require one-fourth the energy to lift the vehicle.[36] The MLU-001 was also designed to carry a few passengers, so that the comfort of the ride could be measured in a qualitative manner, and so that visiting dignitaries could experience first hand this new form of transportation. And this later proved important in helping to preserve the future of this project.

As the design of the car evolved closer and closer to that of an eventual commercial design the engineers at the JNR research laboratory found themselves increasingly in a dilemma. Although elated at the success of its project, the R&D staff became increasingly pressed about what to do next. Linear motor car technology could, for example, deliver even higher speeds, but the track at Miyazaki was too short to go much beyond the 500 km/hr target, a longer track would be needed. Further development of the vehicle would involve incremental design and testing improvements which would advance it toward commercialization, but demonstration for commercialization would increasingly link the project to the desire by the government to build the linear motor car system. And this commitment was not clear.

Through the next five years, developmental work continued on the linear motor car, but at a reduced pace.[37] Many of the tests conducted during this time were designed to improve the operational characteristics of the vehicle and included tests of the ability to control the multi-car vehicles, of the emergency braking system in the instance of partial or complete quenching of the superconducting coils, and of the ability of the vehicle to tolerate nonuniformities, staggers and bends in the guideway - nonuniformities which would derail conventional rail cars.

In 1987, the next incremental step was completed with the unveiling of the MLU-002. The design of this prototype was intended to be close to that of the anticipated commercial model. The car was 22 m in length, about twice as long as any of the previous models, and had 44 seats installed for passengers.[38] The number of magnets were reduced and placed away from the passenger area at the front and back ends of the car. Although these magnets would also be magnetically shielded from the interior of the vehicles, they were located away from the passenger areas to further reduce concerns that unexpected

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[36] "8 ji Koiru Sayo," Nikkei Sangyo Shimbun, January 10, 1991, p.5.

[37] Budgets for overall development at the JR Technical Institute and for support by the government both show a steady decrease through the mid-1980's, with support to about a third of the peak values at the end of the 1970's.

[38] The commercial vehicle is expected to have a seating capacity of 96, but in the case of the MLU-002, about half of the floor area was reserved for testing equipment.

intrusion of a magnetic field might adversely affect pacemakers, or other electronic products that passengers might bring aboard. The body has also been streamlined to further reduce aerodynamic drag and noise, with window recesses eliminated and the exterior panels welded to the body rather than riveted.

However, over the decade, enthusiasm over the project gradually waned and as time wore on without decision to proceed with the next step in development, clouds of pessimism began to form over the future of the linear motor car.

The evolution in linear motor car prototypes up to this point is summarized in Table 4.

## The Political Decisions

We saw earlier that the project was given its initial boost in support not from a technical breakthrough but from the desire of JNR to use the prototype as an attraction in supporting its 100th Anniversary celebration. Its success led to the commitment of funds for the Miyazaki test facility, which allowed engineers to successfully show that a prototype could achieve a 500 km/hr speed goal. The next major step toward commercialization would require the construction of a longer track for full vehicle testing. It was estimated that a track approximately 50 km would be needed. This would be expensive. This would require work on the scale of a public works project, and for such a project political support proved critical.

The general mood of the government in the mid-1980's was one of budget cutting not budget growth. In addition, in April of 1987, the national railway was privatized and divided into 6 regional private organizations. By this time the JNR had accumulated a debt in excess of 37.1 trillion yen ($ 256 billion),[39] and in the midst of the cost cutting and debt forgiving that attended privatization, there was not a high level of enthusiasm for embarking on a new and very costly project.

During this period, there were many who predicted that the linear motor car project would be shelved for an indefinite period. Funds developed at the laboratory and those committed directly by the government were at their lowest levels. During this period, bureaucrats in the Ministry of Transportation were apparently lukewarm in their support of the linear motor car having just emerged from the chore of distributing the long-term debt of the national railway as part of the privatization.

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[39] Unyusho, Unyu Hakusho, Tokyo: Unyusho, 1987, p.147. The dollar conversion was made at the 1987 IMF rate of 144.6 yen/dollar.

Table 4. Characteristics of the Linear Motor Car Prototypes[40]

| Prototype | System | | Length (m) | Mass (tons) | Coil Power and Number | Speed (km/hr) | Year |
|---|---|---|---|---|---|---|---|
| LSM 200 | LSM | MG | 4.0 | 2.0 | 320 kA x 2 | 50 | 1972 |
| ML 100 | LIM | MG | 7.0 | 3.5 | 250 kA x 4 | 60 | 1972 |
| ML 100A | LSM | NFG | 5.0 | 3.6 | 160 kA x 4, 450 kA x 4 | 60 | 1975 |
| ML 500 | LSM | NFM | 13.5 | 10.0 | 250 kA x 8, 450 kA x 8 | 517 | 1977 |
| ML 500R | LSM | NFM | 12.6 | 12.7 | 250 kA x 8, 450 kA x 8 | 204 | 1979 |
| MLU 001 | LSM | NFM | 10.0 | 10.0 | 700 kA x 8 | 405 | 1980-82 |
| MLU 002 | LSM | NFM | 22.0 | 17.0 | 700 kA x 8 | 420* | 1987 |

| | | | |
|---|---|---|---|
| LSM | Linear Synchronous Motor | NFM | Null-flux magnetic guidance |
| LIM | Linear Induction Motor | * | Planned (at time of the referenced article) |
| MG | Mechanical Guidance | | |

Realizing the danger to the project and to the public works funds that would attend the project, a variety of groups activated to keep the fire alive. Academics, bureaucrats, and staff of the newly privatized Railway Technical Research Institute (RTRI) argued that the technology had by now been largely proven, the nation's future transportation needs would greatly benefit from its completion, and that it was a chance to display to the world the advanced state of Japan's technology.

For the prefectures in which the site would be located, this would mean major public works projects, bringing in new money, creating jobs, and raising the level of salience of the region nationally and internationally.

Regional groups were established to conduct feasibility studies for locating the test site and initially 17 proposals were received. By 1989, three sites emerged as the most likely candidates: Miyazaki, Niigata, and Sapporo. One group argued that the easiest alternative would be to extend the existing 7 km track at Miyazaki. The testing facilities that had been used over the past decade were already sited at Miyazaki so it would avoid the logistic problems that would be associated with moving. Some academics also argued that by keeping the facility in Miyazaki, where it would principally designed as a test facility, there would be fewer pressures to initiate commercial service prematurely. This, it was argued, was a potential problem with the other two options.

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[40] Hisashi Tanaka, "Application of Superconductivity to Transportation: Magnetically Levitated Train," p. 61, First International Conference on Superconductivity, Nagoya, Japan, August 28-31, 1988.

A second group pressed for citing the test track between the Chitose Airport (also known as Sapporo International Airport) in Hokkaido and the city of Sapporo. This was about the appropriate length for the testing desired and it would allow the linear motor car to be quickly converted into commercial operation.

The third group argued that since the principal route toward which the linear motor car would be targeted is Tokyo - Osaka, then the test track should be placed in this corridor, again to speed the eventual commercialization of the technology. As the Shinkansen was already serving the coastal areas between Tokyo and Osaka, it was argued that the route should be planned through the inland regions, an argument, which will be explained later, may have worked well in developing key political support for this project.

The Tokyo-Osaka group could make the greatest argument of pressing need. The Shinkansen system, for example, would have to undergo repairs of its infrastructure, its bridges and elevated track by the end of the century, forcing its closure for days at a time. Furthermore, the Shinkansen was already near capacity. In its opening year it averaged 11,000 passengers per day, and by 1990 the daily passenger load had increased to 27,000. The "Hikari" (super express) between Tokyo and Osaka now runs at 85% capacity on average, but rises to 110-120% during rush hour and 160% on Friday nights.[41]

While all of these arguments may be rationally persuasive and true, the decision to supply the funds necessary for the next phase was a political decision. More importantly, politicians were realizing that the cancellation of the project would mean the lost opportunity for bringing public works funds to one's district. The Mitsubishi Research Institute has estimated that the construction of the central linear Shinkansen between Tokyo and Osaka would require an investment of 3 to 4 trillion yen, with other estimates going as high as 10 trillion yen.[42]

The financial gain to one's district and to local industry lies not just in the value of the construction project, of course, but also in spin off effects such as rising land values, increased tourism, and work created by the investment of the district to attract the project. It was reported that some agricultural land in Yamanashi which had been selling for 20,000 to 30,000 yen per 3.3 square meters before the project seemed likely, had skyrocketed in one year to 300,000 to 400,000 yen.[43] The average value of land near the stations increased an average of 40-70% after the announcement.[44] In addition, tourism generated from attracting guests from around the world to the test site is expected to generate another

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[41] "Jisoku 500 kiro no Yume Nose Chaku Chaku," Asahi Shimbun, March 21, 1989, p.14.

[42] "Hiyou Futan ni Karamu Omowaku," Asahi Shimbun, August 8, 1989, p.4.

[43] "Yuchi Mikoshi Tochi Touki," Asahi Shimbun, April 9, 1989.

[44] Conversation with representative from the Land Planning Agency.

one trillion yen.[45] And further, to attract the project, Yamanashi prefecture promised the commitment of 5 billion yen to the improvement of roads and public facilities.

It is no coincidence, in light of this, that on July 17, a day before a closely contested lower house election between an LDP and opposition party candidate in Yamanashi, the Minister of Transport, Yamamura, pre-empted the official announcement of his own Ministry by announcing that they would be requesting funds to initiate the next phase of the linear motor car in the following year.[46]

On August 3, 1989, the Ministry of Transportation announced that they had approved a plan and budget for the construction and operation of the test site valued at 350 billion yen. 260 billion yen is directed to the track construction which is expected to take 5 years, and 90 billion to testing and development which is scheduled for 3 years.[47] It was noted that the expected site would be in Yamanashi, but the formal definition of the site was to follow four days later through the August 7 announcement of the advisory committee.

The timing of these two announcements may seem strange at first, with the budget announcement preceding the formal recommendation of the advisory committee. But this reveals a commonly practiced technique when a potentially controversial decision is about to be made. On the date of the budget announcement, both the Transport Minister and the Ministry's head of the linear motor car project were away from Tokyo. If strong, unexpected opposition was voiced to the choice of Yamanashi, they and the advisory committee had room to claim that the budget announcement was an unauthorized act by a lower bureaucrat. They would have time to retract the decision and apologize for the misunderstanding. Since unanticipated objections did not arise, however, the decision of the advisory committee came as planned: the course would travel 43 kilometers between Akiyama and Sakaigawa villages in Yamanashi prefecture.

Whose argument was most influential is unclear, but two politicians have been visible in claiming credit, Shintaro Ishihara and Shin Kanemaru. Ishihara, the Minister of Transportation in 1987, has argued that the continuation of the linear motor car project resulted largely from his personal guidance to the ministry. As Minister, Ishihara visited the Miyazaki test facility and a rode on the MLU-001. He was enamored by the technology and more importantly by the claim that Japan's linear motor car technology was currently leading the world, a lead that would disappear should funding for the project cease.

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[45] "Rinia de 'Kasegu' ' Waka' Yamanashi," Asahi Shimbun, October 31, 1989, p.3.

[46] "Hiyou Futan ni Karamu Omowaku," p.4.

[47] "Rinia Jikken Yamagata de," Asahi Shimbun, August 4, 1989, p.3. Of this figure, the government will provide 30 billion yen, JR Tokai will provide 150 billion yen, and the remainder will be provided by the regional railways. (Conversation with Land Planning Agency officials in December of 1990 reveals that the government burden has increased to 49 billion yen.)

Ishihara then became an advocate for the technology, with the hope that it would bring prestige to the country and could be transferred to other nations commercially and through international contribution. Both he and bureaucrats interviewed in the Ministry of Transportation claim that had he not given the Ministry of Transportation the signal to push for this project, it would have died.[48]

More important, however, appears to be the push provided by Shin Kanemaru. Shin Kanemaru, a very senior member of the powerful Takeshita faction in the LDP, represents a constituency in Yamanashi. And it happens that the proposed test site runs through his district, with a nice view of the test site from the golf course above, of which Kanemaru is the Chairman. Kanemaru has been quoted as saying that in return for his support of the project he received a verbal promise from both the Prime Minister and the Ministry of Transportation that the next test facility would be sited in his district.[49] As mentioned earlier, after it was clear that Yamanashi would be the site, land values along the course increased dramatically.

Interestingly, for JR the ultimate benefits to net income are less clear. Simple calculations by the Mitsubishi Research Institute show that although 7 trillion yen in income can be anticipated from the operation of the linear motor car, this income may be more than offset by the interest adjusted 4.3 trillion yen estimated for construction and losses in ridership to the existing Shinkansen. Mitsubishi estimates that a net loss of 1.1 trillion yen will occur when the two systems are considered together.[50] Nonetheless, the political decision has been made to proceed, and because the linear motor car has become more an issue of political support and international standing than economics, the above forecast has not slowed progress.

## Patterns of Innovation

Up to now, I have been describing this activity as the historic evolution of a single entity, the overall project. But it is one to which many firms have contributed. In this section I will examine patterns of innovation which give insight into how the principal firms are organized and how collaboration occurs. How was the R&D managed? What role did collaboration play in development? Is there a pattern in the collaborations? We can

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[48] This claim is generally confirmed by a number of independent sources in the Ministry of Transportation.

[49] Makiko Ogihara, "Boss uses old-time politics in maglev tussle," Japan Economic Journal, March 25, 1989, p.40.

[50] "Chuo Rinia Ekusupuresu Jisoku 500 Kiro no Yume Nose Chaku Chaku," Asahi Shimbun, March 21, 1989, p.4.

get some answer to these questions by looking at the overall pattern of patent submissions by year.

First a brief introduction to what our patents will be analyzing. The linear motor car system essentially consists of a car, a guideway, a propulsion mechanism, and the control system. Through the series of prototype designs, the design of the linear motor test vehicle came closer and closer to approximating the commercial prototype, with improvements in aerodynamic design, weight, and equipment housing. The superconducting magnets and its associated cooling system are mounted on the cars.

The rail structure provides the guideway for the vehicle and houses the conventional magnets which are manipulated for control and levitation. As described earlier, through the ML-500, the car operated by straddling a single I-beam shaped guideway. However, with this arrangement, the cross-sectional area of the car-rail system would be on the order of 25% greater than one designed into a U-shaped track. So beginning with the MLU-001, a U-shaped track design was selected.

Propulsion for this train is provided by a linear synchronous motor, which can be visualized as an unfolded rotary synchronous motor. Again, the superconducting magnets are placed in the vehicle, and conventional magnets, assembled as three-phase propulsion coils, are placed on the track. A current is passed through these propulsion coils which creates a magnetic field, and the force that acts between the propulsion and superconducting coils propels the vehicle. A schematic is shown in Figure 7.

The speed of the vehicle is controlled by varying the frequency (phase) of the three-phase propulsion coils. This is accomplished through a variable frequency control loop which is manipulated by a cyclotron converter. However at high currents and voltages, technologies to allow this control become increasingly unavailable. The linear motor car is expected to require three times the electric supply of the Shinkansen which means that the older control technologies are not directly transferable. At the Miyazaki test track an 18 MVA cycloconverter was constructed, but for the commercial vehicle, a 40 MVA system is desired, and its development remains as a challenge for the project's engineers.

### - *Patent Analysis*

To examine the contribution of cooperative development to this project, all of the patent applications that have been submitted by the Railway Technical Research Institute, alone or jointly with other organizations, will be analyzed. These 432 applications were divided among seven technical categories: 1) superconducting technologies, 2)

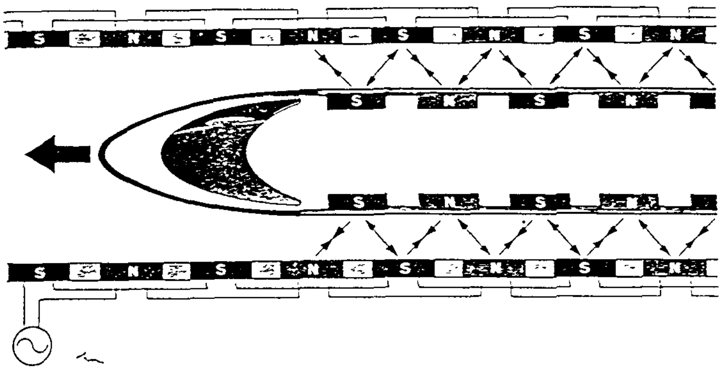


Figure 7. Schematic of the Linear Propulsion System
(From a brochure of the Railway Technical Research Institute.)

conventional magnets, 3) the cooling system, 4) the electrical and control system, 5) the car, 6) the rail and guideway, and 7) miscellaneous test equipment.

Figure 8 shows the peaks and troughs in the level of patent applications related to the linear motor car since 1971. The overall pattern of applications reflects the stages of the linear motor car's development. After the decision was made to develop a high speed prototype in 1970, patent applications displayed a rapid rise, peaking between 1972 and 1975. This activity subsided somewhat in 1976 and 1977 while engineers waited for the completion of the Miyazaki test facility. Activity peaked twice soon after, once in 1978 as engineers prepared for the testing of the ML-500 and ML-500R, and again in 1980 as the MLU-001 and its modified guideway were developed. Through the 1980's we can also see a gradual decrease in patent applications as no major new projects were initiated.

The figure also shows that throughout the program the bulk of the patent applications have addressed innovations in the control and electronic system, with a particular dominance between 1971 and 1976. Overall, this category accounts for about 47% of the applications with those addressing the the vehicle next at 19% and those addressing the guideway at 13%. Patents directly addressing superconducting magnets accounted for just over 6% of the total.

Most of the patents applications were submitted by firms from two industrial sectors, Cable and Wire and Heavy Electrical Machinery. Firms from both sectors exhibit a significant contribution to patents addressing the electrical and control system, with the Cable and Wire sector the principal contributor in developments for the guideway. Firms in the Heavy Electric sector hold virtually all of the patents addressing the cooling system and all patents applying to the superconducting magnets.

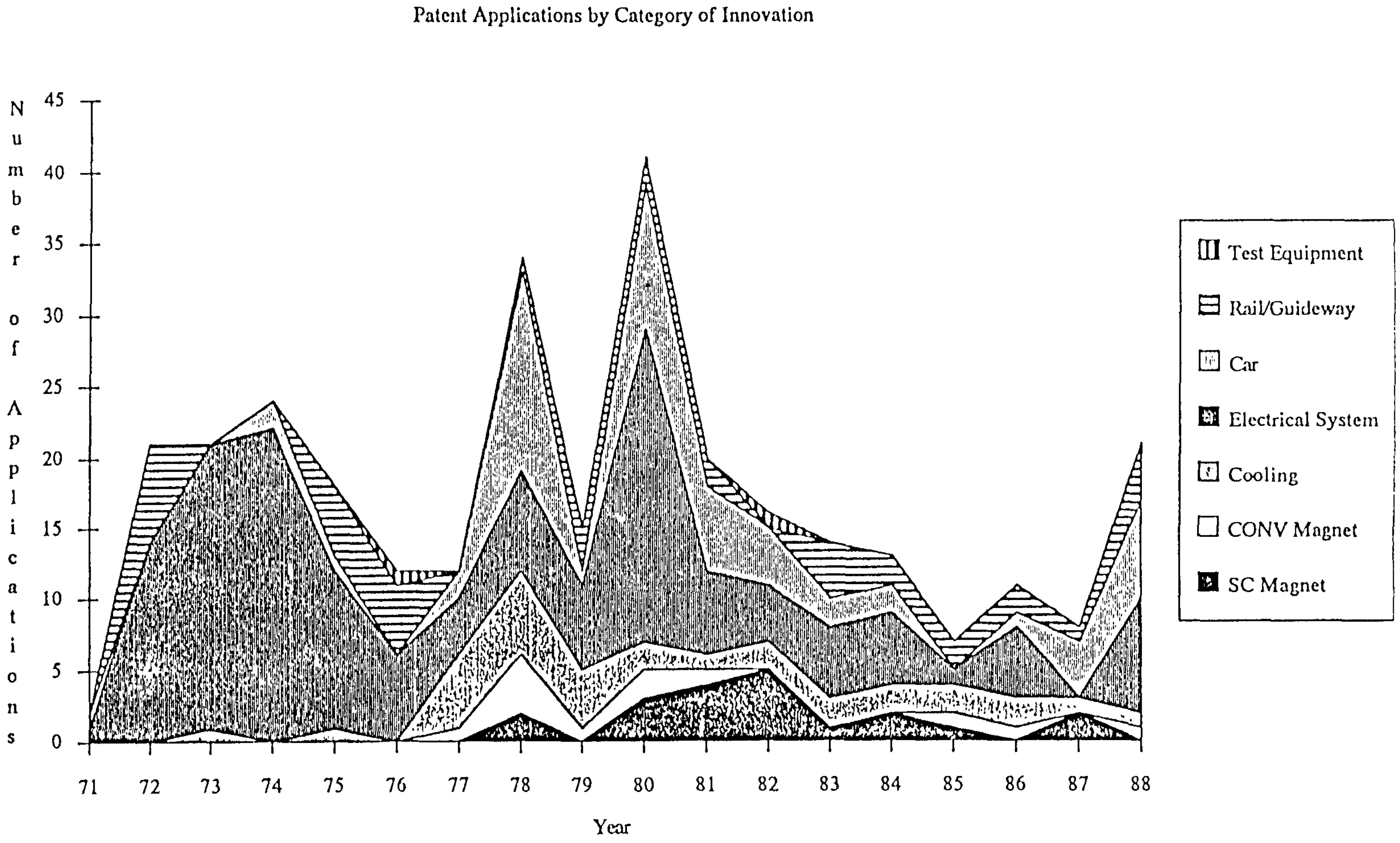


Figure 8. Patent Applications Related to the Linear Motor Car

These sectors have not, however, made equal contributions over time. In the early years of the project, a lot of basic infrastructural work needed to be completed to get the testing complex into operation. During this period the magnetic guideway and the basic control system had to be developed, and for this the Cable and Wire firms provided the greatest contribution. After the basic system was established, further improvements involved development of improved versions of equipment using these facilities, such as the successive versions of the vehicles, and this was the responsibility of firms from the heavy electrical equipment sector. This is seen in Figure 9.

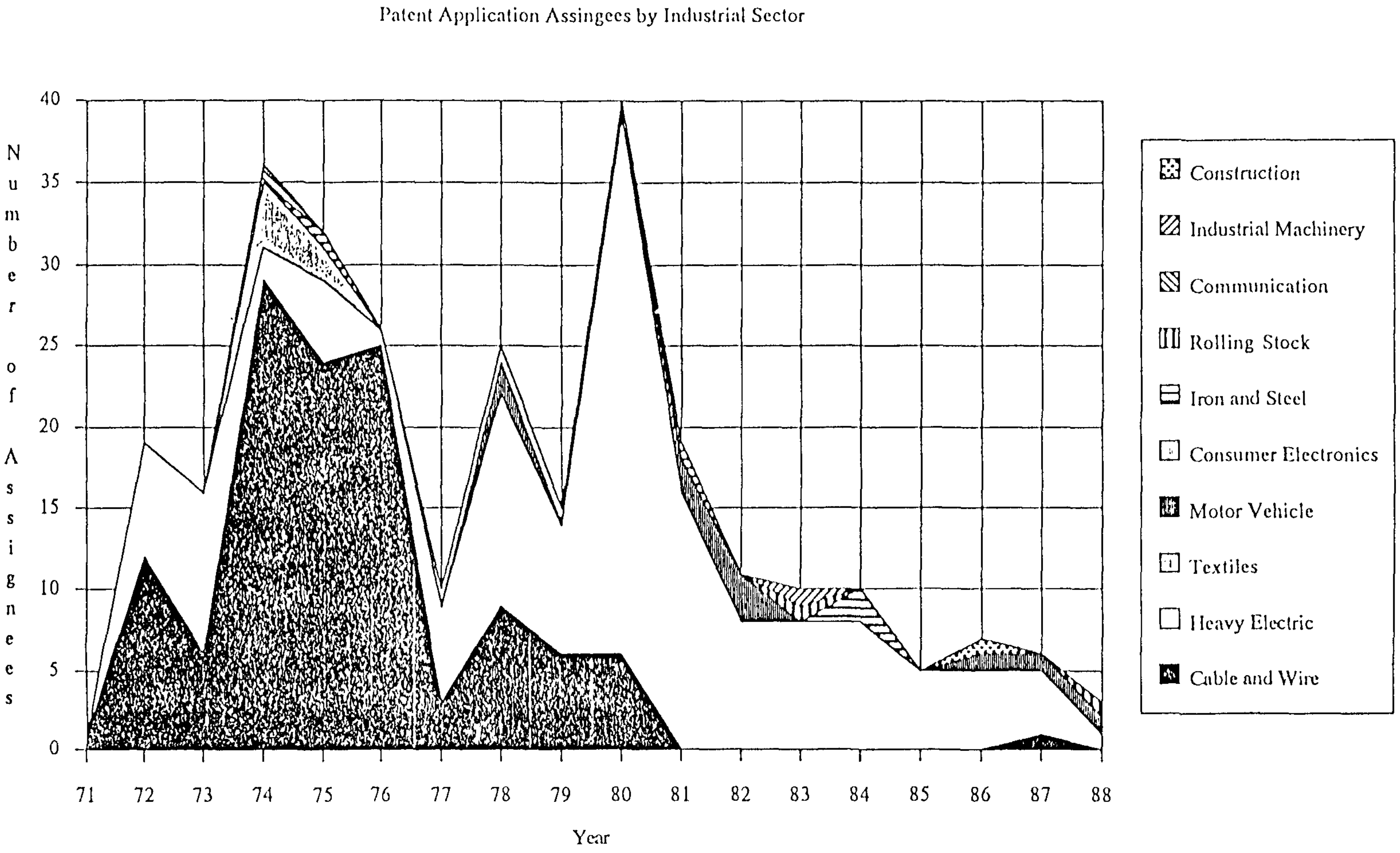
### - *Evidence of Cooperation*

Is there evidence of significant cooperation between these firms in vertical or horizontal relationships? Dividing the patent applications by the number of different organizational assignees, Figure 10 shows that applications between RTRI and a single cooperator was the most common mode over the projects history. However, in the earlier years, between 1973 and 1976, the relative contribution of patents from two or more assignees was a significant portion of the total.

What type of cooperation was occurring? There are three points which emerge from the analysis of cooperation. First, all of the three-firm cooperative patent applications are submitted by the same three firms which are all from the same industrial sector - they are normally commercial competitors. Second, all of the two-firm cooperative patent applications involving firms in different sectors occur with the *keiretsu* of the large firm, and third, technology leadership by the main equipment firms on the development of the superconducting magnets was alternated and was not taken jointly.

Among the applications involving three assignees, all were submitted by the same set of three Cable and Wire firms: Furukawa, Hitachi Cable, and Sumitomo Electric. The reasons for this pattern of cooperation between potential competitors appears to stem form the needs of the technology, the level of inexperience of each of the firms, and the threat of exclusion from the project should they engage in competitive behavior detrimental to the goals of the project. These three firms primarily cooperated on the development of high power switching needed to control the vehicle. This was a single component of the infrastructure of the system. To accomplish this, engineers from each of the firms were dispatched to the site and to the Tokyo laboratory to assist in the system's development, and the engineers worked in a common team for the technical development. As a discreet component intended principally for the test control system, incentives to appropriate

Figure 9. Patent Applications Related to the Linear Motor Car Program by Industrial Sector



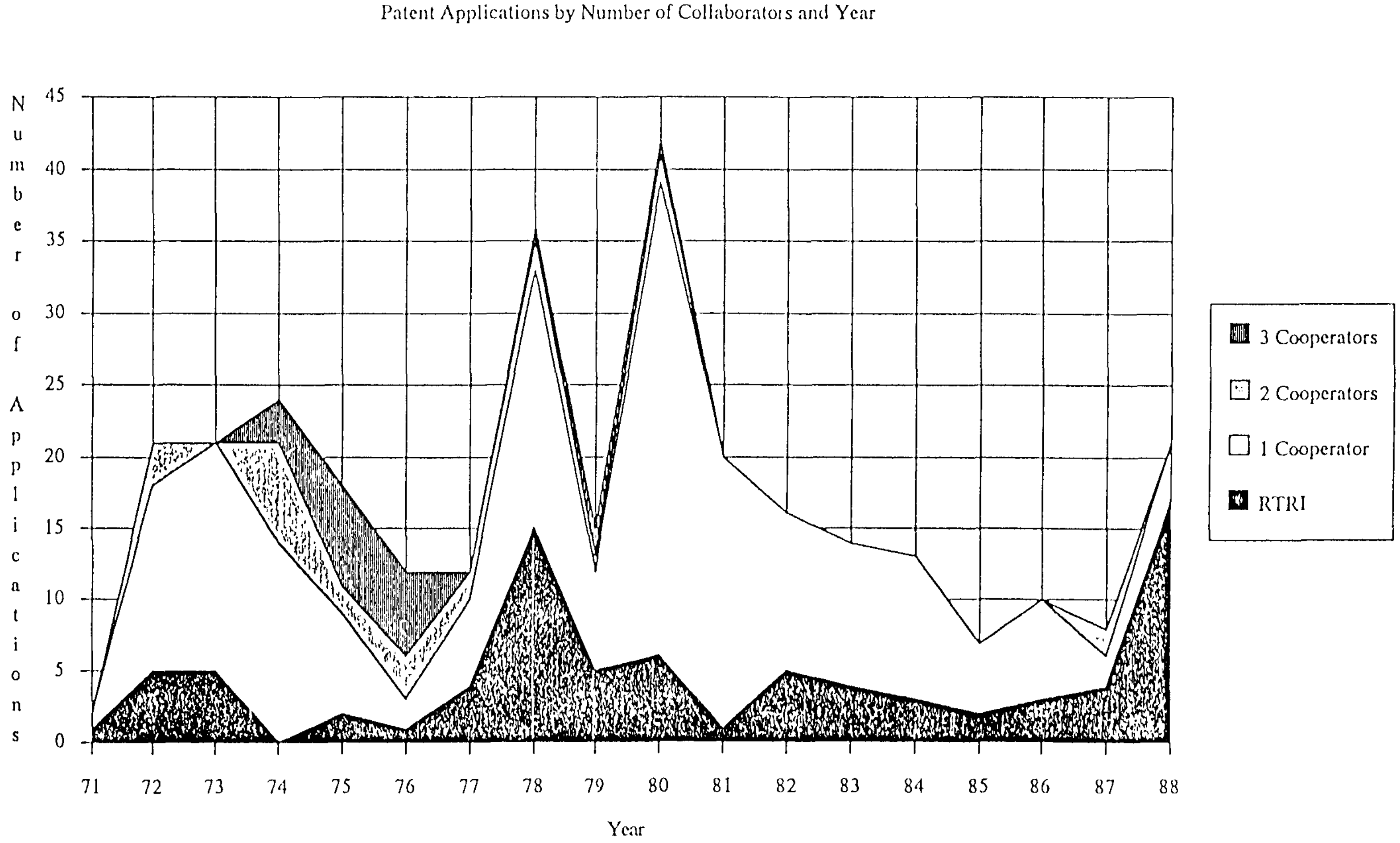


Figure 10. Patent Applications Related to the Linear Motor Car Program by Number of Assignees

advances for future commercial development had less meaning as this project was the main market.

Secondly, in the beginning, all firms were equally inexperienced in this technology and thus no firm was in a position to claim a dominant role. The firms could therefore gain more equally from their experience in the project and the disincentives associated with a strong firm giving up more than a weaker firm were not important. Thirdly, the market for their work would also be, for the long-term, this one project. Competitive maneuvering for their individual interest which would negatively influence the operation of the program, would more likely result in exclusion from rather than exclusive occupation within the project. Other Cable and Wire firms were not allowed to participate, but could should one of the selected three fail to perform. The privilege of participation also meant the promise of cooperation.

Examining the patent applications produced cooperatively by these three firms provides evidence that the degree of cooperation was determined by the companies based on technology need rather than on "cooperative behavior" or on orders to cooperate by the sponsoring organization. Using the rational choice model of Kodama and Kobayashi,[51] we see a pattern of cooperation which reflects the predicted behavior of competitive firms cooperating on a technology project. Using a probability density function based on an assumption of independent decisions to cooperate by each of the firms, their model would predict the greatest number of cooperative cases to occur with single firms and RTRI, followed in number by all three firms, with two firms cooperating being the least likely case. Figure 11 shows that this is the pattern observed here, making it possible to argue that the decision to cooperate was a technologically determined one rather than a coerced one.[52] Insulation was provided from other outside, with discretion to cooperate as needed provided inside.

This is confirmed by engineers at RTRI who point to the commonality of their tasks and the collective but flexible management of firm participation. As the basic infrastructure requiring cooperation was developed, cooperation between these firms can be seen to decrease, so that through the 1980's there were no such cases recorded.

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[51] Fumio Kodama, "Rivals' Participating in Collective Research: Its Economic and Technological Rationale," presented at the International Conference on Science and Technology, What Should be Done? What Can be Done? February 2-4, 1990, Shimoda, Japan.

[52] The intuitive solution would be that as the number of firms increased the number of jointed developed patents would decrease, a constantly declining curve, but the Kodama-Kobayashi Model shows that rational selection gives a counterintuitive result. The political solution would be for all firms to share the patents to maximize diffusion, a largely bimodal curve, but this is also not what is seen.

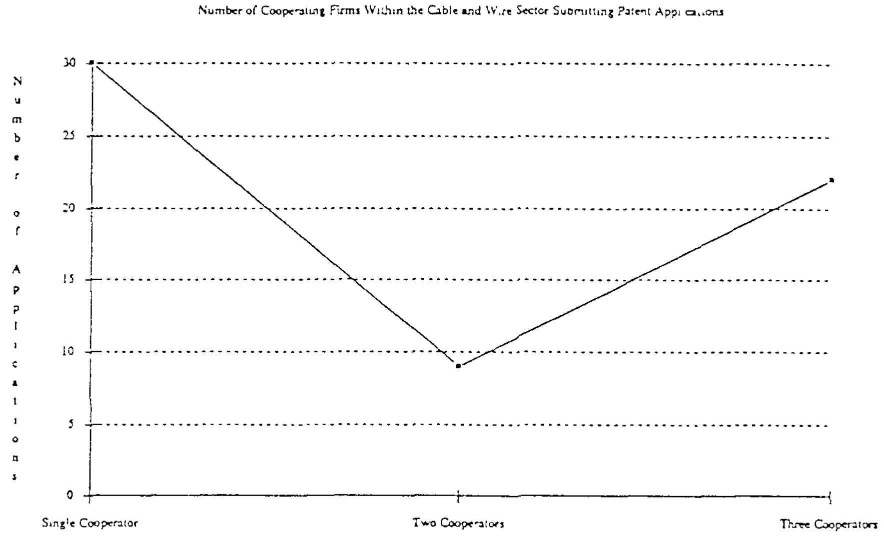


Figure 11. Collaborations Among Competitors

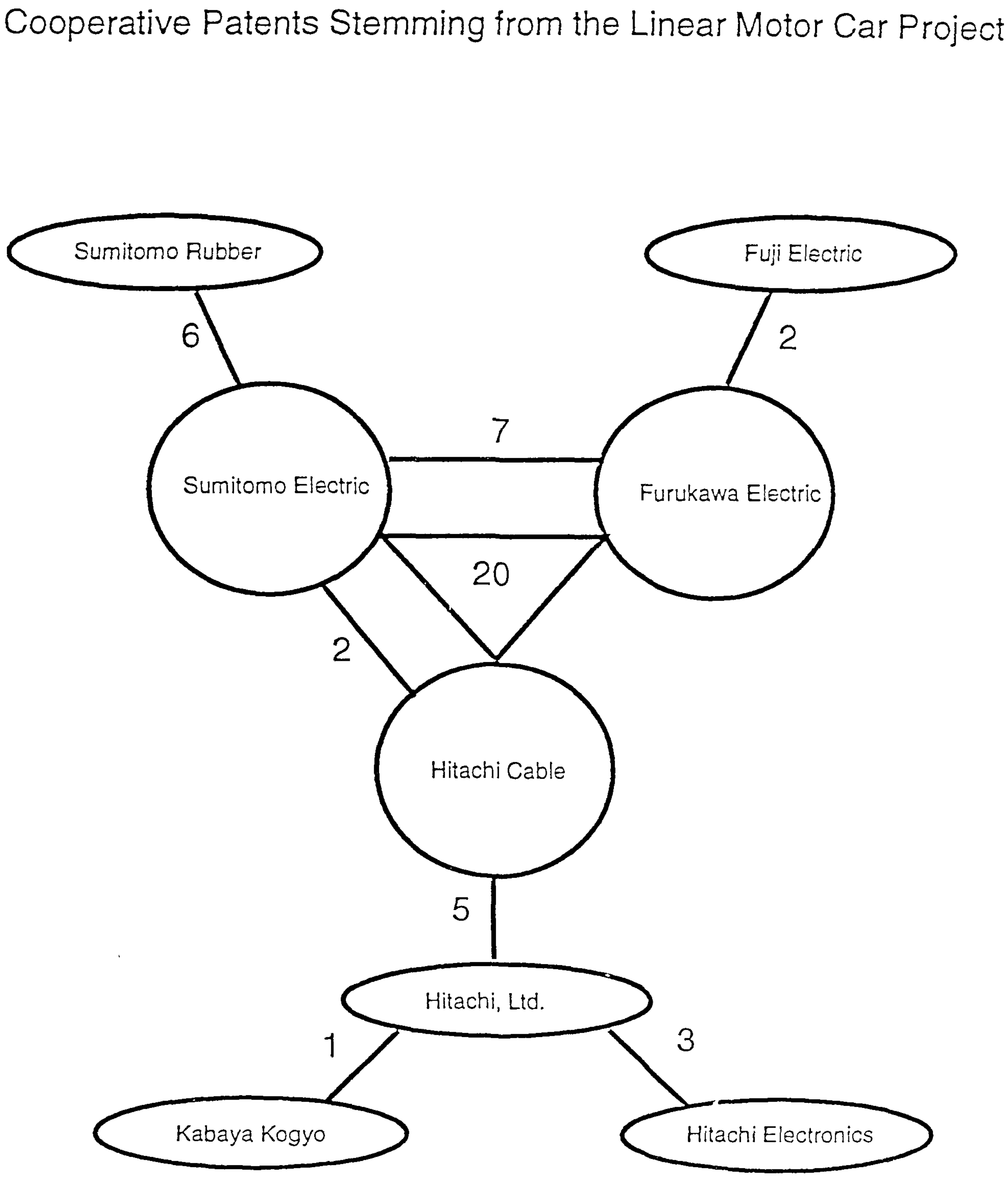
- *Influence of Keiretsu*

Cooperation is also seen to occur between two firms and RTRI outside of the above triangle of Cable and Wire firms. Do these cases seem to represent a freer form of participation? All of these other two firm collaborations also occur in the early years of the project and involve firms cooperating across different industrial sectors, implying a complementary of skills. However, Figure 12 shows that these two-firm collaborations do follow a distinct pattern which would contradict arguments that collaboration was occurring freely.

The three Cable and Wire manufacturers are again central as they represent three different *keiretsu*. The two-firm collaborations all occur within one of these *keiretsu* groupings. There are no examples of firms collaborating across these groupings except for the Cable and Wire firms.

Thus cooperation between two or more firms is seen to be concentrated in the early phase of this project ,with collaboration between firms in the same sector a dominant cooperative mode for three-firm activities. Across sectors, firms are seen to reach for complementary assets through two-firm cooperation, but always turn to their *keiretsu* affiliates rather than to a varied assortment of suppliers.

Figure 12 Inter-firm Collaborations in Patent Applications Related to the Linear Motor Car Program



### - *Managing Competition in Developing the Superconducting Magnets*

Finally, what about the development of the superconducting magnet itself? As mentioned earlier, patent applications that apply to the superconducting magnets amount to only 6% of all of the patents in the RTRI data set. Does the data tell us anything interesting about the management of collaboration?

Although the data are sparse, it does show that three firms were involved in the development of the superconductors and that Hitachi and Toshiba were more active in submitting applications early in the program, with Mitsubishi Electric the most active later in the program. Interestingly, although there were three cable manufacturers capable of supplying the superconducting wire and more than three device manufacturers capable of producing the magnets, there were no cooperative patents submitted, indicating that the basic manufacturing technology was based on largely established technology.

Conversations with engineers at RTRI reveal that this hint of information is revealing of their management strategy in developing this technology. They selected the three most capable private sector superconducting magnet manufacturers but the firms did not work in a common facility as 1) there was not a technological need to do so, and 2) they preferred not to work together. Thus RTRI had the firms alternatively take the lead in being the main developer of each of the superconducting prototypes. For the LSM-200, Toshiba was the principal developer. For the ML-100 Hitachi was the main developer. The lead then changed to Mitsubishi for the ML-500, to Toshiba for the MLU-001 and to all three firms for the MLU-002. The plan on the part of RTRI was to have several firms capable of supplying this technology so that 1) they would press each other in increasing the level of the technology, 2) they would not be overly dependent on a single source, and 3) they would gain from the work of the others through an alternation of the technical lead, and thus a transfer of information, in a continuously developing technology. By employing several competing firms work on the same technology area, firms can speed development through a ratcheting up effect. By alternating the technological lead, information is diffused from one firm to the next, providing for collective learning in an insulated structure. By contracting with several firms, also RTRI better assured that there would be a diffusion of the technology to each firm's subcontractors and suppliers and thus a wider technology base upon which it could rely.

When the lead shifted to Mitsubishi, Hitachi decided that the market for this opportunity was going to be too small for too long and decided to switch its focus to other applications, primarily fusion test magnets, dropping out, for the time being from the superconducting magnet portion of the project. This is evidenced in the patent applications.

Table 5 shows that steady progress was made to make the magnets more powerful and more compact. The wall magnets for the MLU-001 and 002 are strong enough to provide all three functions of levitation, propulsion, and guidance, and the number of magnets have been gradually reduced so that they can be positioned at the ends of the cars, away from the passengers. However, floor magnets have still been used in the cars and on the guideway for added stability. For the next prototype, these floor magnets will be eliminated, leaving only the wall magnets to provide for operation. This is expected to reduce the electricity consumption by 10%.[53] For this task, all three manufacturers have been activated and requested to conduct developmental work independently. Thus for development in this final phase, RTRI is hoping to exploit competitive incentives among project participants to achieve higher program performance.

- *Remaining Challenges*

Before the project is completed, however, much remains to be tested in the demonstration phase and new opportunities for improved performance loom to be explored. The reliability of the magnets, for example, has to be confirmed in an actual

Table 5. Features of Superconducting Magnets Used in the Linear Motor Car Prototypes[54]

| | LSM* (1972) | ML-100* (1972) | ML-500 (1977) | MLU-001 (1980) | MLU-002 (1987) |
|---|---|---|---|---|---|
| Weight of Wire | 73 kg | 66 kg | 116 kg | 100 kg | 77 kg |
| Magnetomotive Force | 320 kA | 250 kA | 450 kA | 700 kA | 700 kA |
| Number of Coil Turns | 230 | 355 | 560 | 1000 | 1167 |
| Electric Current Density (A/mm$^2$) | 112 | 121 | 89 | 183 | 210 |
| Stored Energy | 77 kJ | 48 kJ | 196 kJ | 522 kJ | 550 kJ |
| Maximum Magnetic Field | 2.1 | 1.9 | 2.9 T | 4.7 T | 5.1 T |
| Copper Ratio | 6.7:0 | 8.5:0 | 7:0 | 2:0 | 1:0 |
| Number of Core Wires | 230 | 355 | 253 | 2257 | 2689 |
| Maglev force/ One Magnet | 400 kg | 950 kg | 2,500 kg | 2,500 kg | 4,250 kg |
| Maglev force/ Magnet Weight | 0.32 | 0.95 | 1.8 | 3.9 | 4.5 |

* Recall that these are much smaller vehicles than the later prototypes.

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[53] "Sokuheki Fujoushiki Rinia Saiyo, Shouhi Denryoku 10% Gen," Nikkei Sangyou Shimbun, August 8, 1990, p. 1.

[54] M. Yamaji and H. Nakashima, "Superconducting Magnet for Magnetically Levitated Vehicle," First International Symposium on Superconductivity, Nagoya, Japan, August 28-31, 1988, pp. 71-76; and "Fujoshiki Tetsudo no Chodendo Kyokuteion Gijutsu," Teion Kogaku, Vol. 16, No. 5, 1981, p. 274.

operating environment. In operation, the vibration of the train tends to heat the magnets, which could case a quenching of the superconducting phenomena and hence a sudden loss of power. This would result in a sudden loss of power that would cause the train to veer into the wall of the track, as happened during a test run at the end of May 1990.[55]

The performance of the vehicle entering and travelling through tunnels will also be an important test given the high speeds of the train and estimates that 60-80% of its path between Tokyo and Osaka will be through tunnels. And perhaps most importantly, travellers will have to feel comfortable that the strong magnetic fields generated by the magnets will not be a danger to their health.

The discovery of high temperature superconductivity also presents new opportunities as the use of HTS magnets in the linear motor car would in theory reduce energy consumption through a 10-15% reduction in vehicle weight and a 5-10% reduction in on board vehicle needs.[56] However, this possibility has had little effect on the program design to date. It is generally felt that the availability of high field HTS magnets is still a large number of years in the offing, so the program is focussing on continued development of LTS magnet designs.

Where HTS materials may play a role is in magnetic shielding. This technology, it is believed, will be available by the mid-1990's, and its use would allow some reduction in refrigeration costs and weight.

### Summary

In large public technology projects, politics will come to play an important role in Japan as in any other country. In the case of the linear motor car, the incentives and decisions of politicians appear to have been instrumental in keeping the program in existence and in determining the pace of development. Like any public works project, it means increased employment and increased land value. But the reach of political intervention is not deep. As a technology project, RTRI and its contracting firms were allowed to focus primarily on each prototype goal, organizing the firms to exploit competitive and cooperative incentives in development.

In managing the development of the linear motor car, a salient feature which is observed through the program is the use of multiple contractors for the main technology

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[55] "Rinia Jikkensha ga Jiko," Yomiuri Shimbun (yukan), August 28, 1990, p. 18; with more details in "Masatsunetsu de Jiryoku Ushinau," Nikkei Shimbun, September 3, 1990.

[56] Donald Rote and Larry Johnson, "Potential Benefits of Superconductivity Transportation in the United States," First International Conference in High Temperature Superconductivity, August 28-30, 1988, Nagoya, Japan, pp. 66-70 (67).

development tasks. At a minimum, multiple sources act as a form of insurance, in case one of the firms could not perform as expected, or in case one of the firms becomes disinterested in some part of the development activity. The latter, for example, was seen to be the case with Hitachi, as it dropped out of the superconductor magnet development after the ML-100 prototype. Multiple sourcing was also a way of instilling competition in development, providing a disincentive to shoddy or lethargic work, and a means of leveraging the capabilities of several firms by diffusing information through joint tasks or alternating project leadership.

However the use of multiple firms does not always mean that the program was expecting or forcing cooperation. Cooperation or competition are used in accordance with the appeal of the technical and competitive incentives, and reflected existing industrial relationships. Cooperation evidenced in joint patent applications occurred where the technology targeted was one of common infrastructure and the level of experience equal and low enough that each firm had little to lose and continued participation to gain from the collaboration. This was seen in joint patent applications by the three participating cable and wire manufacturers in the development of power controls early in the project. After this, the need was filled, the cooperation dissolved and did not reemerge for the rest of the program.

Cooperation between firms in different sectors was also seen in the patent application data, but all cases occurred between firms in the same traditional industrial grouping, or *keiretsu*. Here each of the cable and wire manufactures were seen to be cooperating in its own set of subcontractors. A free association of two-way, inter-sector cooperation was not observed.

When the development of the superconducting magnets are examined, however, we see that the three major systems firms were managed for competition rather than cooperation. Each firm was capable on its own of producing the needed superconducting magnets, and so each firm was allowed to do so, alternatively. The progressive advance of the prototypes required continued advances of these magnets as described earlier, and this kept the firms in search of improvements.

Thus in this linear motor car program, cooperation was seen to be limited, grouped and internally rational. It is limited to a selected set of Cable and Wire manufacturers and Heavy Electrical Equipment firms, the prime contractors. It is grouped among the *keiretsu* of the major participants to take advantage of established norms of cross-sector cooperation to enhance the contribution of each prime contractor. And it is internally rational in the sense that project selection for cooperation within these grouped firms appears based primarily on technical motivations within the constraints to appropriation present because the client is national a singular, not commercial and multiple.

Finally, even though from the beginning this project was and still is hailed as a project that centers around an advanced technology, superconductivity, no new developments in superconducting magnets were needed for the first two prototypes. The project exploited existing technology. It was not until 1978 and the ML-500 that the first patent applications in superconductivity were submitted, and as we have seen from the data of improved magnet performance, these advances have been incremental ones in improving the power to weight ratio of the devices.

## IV. WHAT WAS THE INDUSTRY STATUS AT THE TIME OF HTS

As described in the earlier section, there was a history of technology development activities which contributed to the creation and sustainability of a LTS industry and which provided for an HTS research capability at the time of its discovery. The purpose of this section is to review the status of the industry at the time of the discovery, to provide some sense of the capabilities that could be drawn upon, of the industrial structure and relationships which existed, and to shed light on the opportunities or needs for government policy and cooperative R&D.

### The LTS Markets

As described in the discussion of the history of this technology, during the period between 1970 and the mid-1980's much of the market was directed toward providing wires to accelerators, fusion and magnetic field experimental devices. Magnets for the linear motor car experiments and university laboratories were also being delivered, but the market size was far more minor. During this period, the superconducting wire market in Japan averaged one hundred million yen ($1-2 million) per year.

In the mid-1980's, Japanese makers entered the commercial market for Magnetic Resonance Imaging systems, which provided a boost to the industry. In October 1985, there were 48 MRI units operating in Japan, with more than two-thirds of these using conventional magnets. By September of 1988, the number of installed united had grown to 351, with less than a quarter using conventional magnets and 60% using superconducting magnets. At this time the superconducting systems were priced at 2-5 hundred million yen per set. By November of 1989, there were 643 MRI machines operating in Japan, of

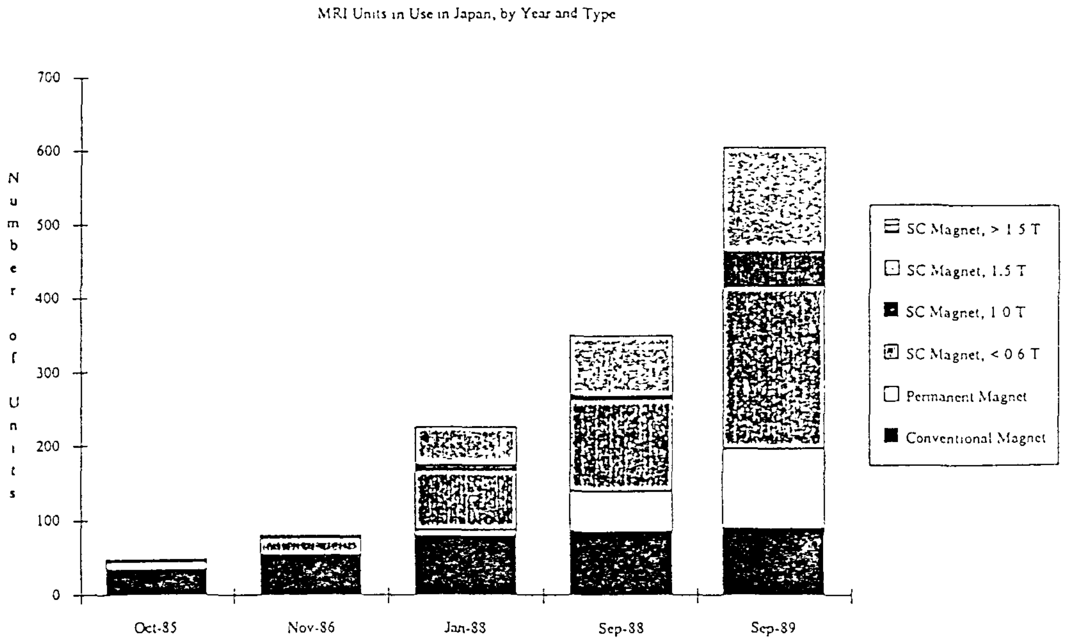

Figure 13. Growth in the MRI Market in Japan
(From "MRI Sochi Settchi Byoin Ichiran," Eizo Joho Medikaru, Rinjizokango, Vol. 21, No. 24, 1989, p. 214.)

which about two-thirds now used superconducting magnets - exactly the reverse of the ratio four years before when the market was just opening. Figure 13 shows this growth in the MRI market and the use of superconducting magnets.[57] The figure also shows that much of the growth has occurred in two submarkets: smaller, low field machines rated at less than 0.6 T, and 1.5 T high field magnets. Intermediate sized magnets and very large magnets occupy a much smaller share. With the increase in volume and experience, the cost of these MRI units have been brought down to 1-2 hundred million yen per set.

In contrast with U.S. manufacturers who have targeted the higher strength machines, the Japanese have a stronger capability in the smaller sized machines. For many applications, such as orthopedics, the smaller machines are considered more than adequate and have the added attractiveness of being less expensive, easier to install, and take up less space. This makes the smaller machines more attractive for the numerous small hospitals around the country.

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[57] "MRI Sochi Settchi Byoin Ichiran," Eizo Joho Medikaru, Rinjizokango, Vol. 21, No. 24, 1989, p. 214.

Toshiba and Hitachi lead Japanese manufacturers, Having sold 158 units each. They are followed by Shimadzu at 105 units, Yokogawa-GE Medical at 93 units, and Siemens-Asahi at 79 units.[58] These latter two companies are joint ventures initiated by firms overseas to penetrate the market in Japan. Yokogawa Electric teamed with GE Medical in 1987 and Siemens tied up with Asahi Chemical in 1989.

Although Japanese companies are strong at home, they are not as strong abroad. Japanese firms have a very small share of the U.S. MRI market, less than 10%, and an even smaller share of the European market. Their overseas competitors such as General Electric, BTi, Oxford Technology, and Siemens, are more technologically advanced than the Japanese firms.

Outside of Japan, some of these manufacturers have allied with firms overseas to help penetrate MRI and related medical markets. In 1989, Toshiba purchased the MRI division of Diasonics Inc. of San Francisco to help further market its machines. Hitachi Ltd. and Philips also tied up in the same year in a joint venture in Concord, Massachusetts to begin manufacturing CT scanners. While Hitachi's presence is small in the U.S. MRI market, Philips had a 7% share in 1990 and Toshiba a 8% share. Although this is still far behind the U.S. leader, GE Medical, its share has fallen slightly from 47% in 1986 to 44% in 1990. With GE Medical, Seimens (22%) and Picker International (11%) combining for 77% of the U.S. market, Japanese firms see room for displacement.[59]

The cost of the superconducting wire is generally estimated at 5-10% the cost of the MRI system, which yields an estimate of 1.5 billion yen for the wire used in MRI devices in Japan. The total superconducting cable and wire market is estimated to be 2.0 billion yen in Japan in 1989.[60] This represents about 25% of the world wide market.

Thus after decades of developmental work on techniques to process the materials into useful wires and cables or films, and then to fabricate the wires and cables or films into useful devices, the LTS market has slowly expanded to penetrate a number of commercial markets. Considering the commercial market as a whole, one estimate is that in 1990, the worldwide consumption of fabricated products which incorporate superconductive materials will be about $54.8 billion. The bulk of this market, $45.1 billion (82%), is in instrumentation and medical devices with other markets including applications in electronic,

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[58] Kazufumi Itoh, "MR Imaging," Look Japan, March 1990, pp.30-31.

[59] Amal Kumar Naj, "GE Aims to Cut Medical Imaging Costs," The Asian Wall Street Journal, September 10, 1990.

[60] Estimate based on conversations with manufacturers. Also referenced was the paper by, Hirohisa Shioda, "R&D on Superconductivity in Japan," Furukawa Electric Company, March 1989, and Strategic Analysis Inc., "Strategic Opportunities in Superconductors: A Global Analysis 1990-2005," July 10, 1990, Reading, PA.

industrial, aerospace and defense, power generation, and transportation. These are summarized in Table 6.

In the early 1990's, the market will continue to grow with the advance of the nation's fusion and particle accelerator facilities as well as through growing markets in miniature Synchrontron Orbital Radiation (SOR) facilities for IC production, cyclotrons for medical process, and SQUIDs for magnetic field measurements. A market in excess of 10 billion yen per year in Japan is anticipated during this period.

### Nature of the Industry

For most of its history, the major markets for superconducting materials have been in speciality order markets much more than commercial markets. Magnets for accelerators, fusion experimental devices, MHD experimental devices, etc., have been the primary uses of the technology. The market operated largely through contracts rather than through generally specified and commercially marketed devices. The main exception to this, again, has been the MRI market which described earlier.

The result of this type of market is that entry can be difficult as capability often weighs heavily in contract evaluation, with experience being vital to capability. First entrants thus have a market advantage. Once their presence is established, they are in a

Table 6. Estimate of the Worldwide Consumption of Fabricated Superconducting Materials - 1990[61]

| End Use Industry | Value (Million $) | Percent of Total |
|---|---|---|
| Instrumentation and Medical | 45.1 | 82 |
| Electronics | 2.7 | 5 |
| Industrial | 2.0 | 4 |
| Aerospace and Defense | 1.7 | 3 |
| Power Generation | 1.7 | 3 |
| Transportation | 1.6 | 3 |

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[61] Strategic Analysis Inc., op.cit.

position to perpetuate this advantage by leveraging their experience and record in future project proposals. With a slow growing and irregular market, the chances for entry are further reduced.

The consequence of this form of market has been that the major players in the industry have been limited over the 30 year commercial history in Japan. A handful of firms have comprised the backbone of the low temperature superconductivity industry in Japan.

The firms active in developing LTS can be generally divided between those that are suppliers of the primary processed materials and those that incorporate these materials into systems and devices, and those that are vertically integrated to do both. As all of the major commercial applications to date have involved forming the superconducting materials into wires, to construct magnets, the firms that have been the locus of materials development and processing have been in the Cable and Wire industrial sector. The superconducting materials developed by companies in this sector are then integrated into devices, again, principally magnets, by firms that have traditionally come from the Heavy Electrical Equipment sector. In the electronics area, superconductivity continues to be almost entirely a research activity, with the exception of a very small market in SQUID devices.

There are eight firms in the Cable and Wire sector that are listed in the first section of the Tokyo Stock Exchange and which dominate most of the cable and wire market. The most active firms in the development of superconducting products are Furukawa Electric, Hitachi Cable, Sumitomo Electric, Showa Cable, and Fujikura. Although no one firm dominates the Japanese market, Furukawa Electric is the largest with close to a 35 % share. This is followed by Hitachi Cable at 25%, and Sumitomo Electric and Showa Cable, each with 15% of the market. These shares are summarized in Table 7.

Because sales in this market are primarily through contracts to large projects, the cycles that a firm must go through can be rather large. One cable and wire manufacturer noted that cycles between projects can mean that twice as many workers need to be reassigned to other projects while they are between orders. Thus a key ton continuing in this industry has been to have the ability to respond to all of the market possibilities within this field.

Of these major cable and wire firms, however, only Furukawa Electric, and to a lesser extent Sumitomo Electric, are totally integrated: only these two firms are involved in the full span of development activities from materials development to systems production. The other firms focus on the materials and cable production processes and work with specific manufacturers to produce systems and devices.

Table 7. Approximate Shares of Superconducting Cable and Wire Market by Major Manufacturers - 1989[62]

| Firm | Approximate Share |
|---|---|
| Furukawa Electric | 35% |
| Hitachi Cable | 25% |
| Sumitomo Electric | 15% |
| Showa Cable | 15% |
| Kobe Steel | 5% |
| Others (Fujikura Cable, etc.) | 5% |

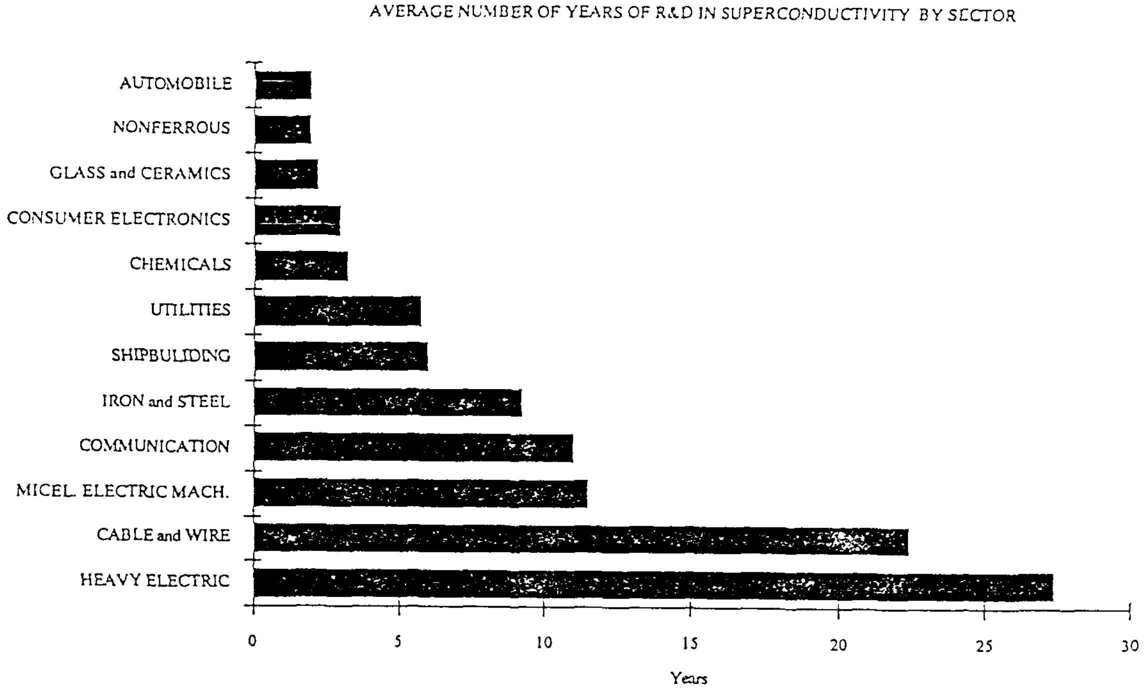

Figure 14. Average Number of Years in Superconductivity, by Industrial Sector

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[62] Estimates based on conversations with manufacturers.

The principal device and systems manufacturers include Mitsubishi Electric, Hitachi Ltd. and Toshiba. Figure 14 shows the average number of years that active firms from various sectors have been involved in superconductivity.[63] The figure shows that the active firms in the Cable and Wire sector had been involved for an average of 22.5 years, with Sumitomo Electric claiming the longest involvement of 30 years. Firms in the Heavy Electrical Equipment sector have been engaged for an average of 27.4 years, with the principal actors, Hitachi, Toshiba and Mitsubishi Electric, all entering between 1958 and 1961. The figure also shows that outside of these few firms and sectors, entry into the field has been much more recent.

### - *Firm Relations*

In the cases of Hitachi, Toshiba and Mitsubishi Electric research began at the systems and device organizations. At the beginning, superconducting materials were most striking for their novelity, and as these companies had established central research laboratories at this same time, they had more of a capability to devote some research time to exploring the properties. As the possibility of manufacturing useful magnets out of these materials was realized, the work was transferred to the cable and wire affiliates or arrangements were made with cable and wire manufacturers so that existing expertise in manufacturing could be exploited to enter this market.

Because of these historical relationships, it is not generally the case that the various cable firms freely negotiate with various systems manufacturers for projects that arise. Instead many of the cable manufacturers sell to specific systems manufacturers with which they work in arrangements that place a higher priority on purchasing from the partner than from other firms. In some cases these pairings generally follow traditional *keiretsu* relationships, and in others they are non-*keiretsu* but stable relationships which have developed over time.

As the Figure 15 shows, Hitachi Cable supplies virtually all of its cable to Hitachi Ltd., and Showa Cable sends its products almost entirely to Toshiba. Both of these links fall within the firms' *keiretsu*. although Sumitomo has some capability to produce devices, it is also the primary supplier for Mitsubishi Electric, in a long-term relationship that is not contained in one *keiretsu*. Similarly, Furukawa Electric also supplies Mitsubishi Electric in

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[63] The data are from a survey of 60 firms conducting research in superconductivity. These organization account for over 90% of the patent applications submitted in superconductivity by firms between January 1987 and the summer of 1988.

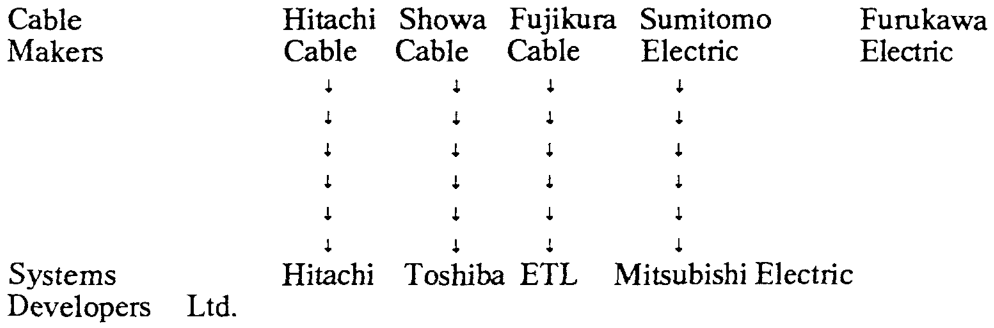

Figure 15. *Keiretsu* and long-term relationships between cable suppliers and systems developers

a non-*keiretsu* relationship, however of all of the firms, Furukawa Electric is the most fully integrated.

For smaller cable and wire firms that have not established these vertical relationships, breaking into the LTS market has been difficult. Contracts with device manufacturers are hard to obtain and the cycles between projects can be severe. As a result, one such manufacturer, Fujikura, has relied principally on its relationship with the government's Electrotechnical Laboratory (ETL) for most of its magnet sales.

Although there are no formal estimates of the size of the *keiretsu* vs. non-*keiretsu* markets, an estimate based on the above relationships is that 40% of superconducting cables and wires exchange hands in *keiretsu*, 30-35% are processed entirely in integrated firms, and 15% are sold in non-*keiretsu* but long term relationships, and 10-15% are sold on the open market.

For the industry, the *keiretsu* and long-term relationships have kept a number of competitors alive in a small market, preventing dominance by a single firm. The competition for contracts has maintained some level of incentives for innovation. However, as the market expands, foreign manufacturers of superconductors will find, like Fujikura, that breaking into this network is difficult. So foreign firms would be expected to come in with devices to sell and through joint ventures with Japanese firms which have these relationships established. This appears to be the case in international joint ventures to produce MRI devices as described earlier. If the wire market itself becomes significant, or if the contracted market suddenly expands from a growth in fusion or accelerator technology, however, we may find that superconductivity may follow in the path of other high technology markets to the international trade table.

- *Research Activity*

In addition to their work in magnets, these principal systems developers are also among the more prominent in research in thin films and electronic applications of the material. This concentration of development activity is reflected in the research budgets reported by the firms responding to the questionnaire. The Heavy Electric Equipment sector reported the greatest level of spending in 1986, prior to the HTS discovery, of 2.25 billion yen, with the Cable and Wire sector next at 1.07 billion yen. Together these sectors represent 62 % of the private sector research investment in LTS. Twenty-six firms having active LTS R&D programs in 1986 reported spending a total of 5.33 billion yen.[64] Figure 16 shows this sectoral concentration of R&D investment. In terms of personnel this translates to a reported 112 researchers in the Heavy Electric Sector and 51 researchers in the Cable and Wire Sector.

When the firms in the iron and steel, shipbuilding, and more purely electronics and communications industry are added, 96.5% of the LTS research in 1986 reported by firms surveyed is covered.

In addition to the research at the main laboratories for the firms in the Heavy Equipment Sector, is also a substantial level of development activity at the production divisions. Firms reported a level of development staff at the divisions that often equalled the research staff at the central laboratories. These individuals are often counted among the production staff and consequently absent from most tallies of R&D activity, and their time may often be spent on small engineering matters. However recognizing their presence provides a more complete picture of the scale of technical activity in the commercialization of this technology. Thus if the R&D staff and the engineering staff are together considered the technical staff, the total would nearly double the sectoral values for R&D staff.

This concentration of innovation in these sectors is also reflected in the patent application data, Figure 17. Data of patent applications announced between 1971 and 1987 for the top 20 patenting firms show that the Heavy Electric sector is dominant with the Cable and Wire firms and the Electronics firms composing the bulk of the remainder.

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[64] An "active firm" is defined as one reporting 2 or more researchers working in research on LTS.

- *In Summary*

Thus at the time of the discovery of HTS, the industry was composed of a number of large, primary materials processors and systems and device developers which represent some of Japan's largest and most successful companies. Although the markets were small, participation by firms was stable over the first two decades. Should materials show promise of commercial use, the networks for producing and diffusing the innovation are already in place. At the same time, HTS offered the opportunity of providing a crack in the insulated superconductor industry.

Figure 16. Sectoral Distribution of Investment in LTS Research

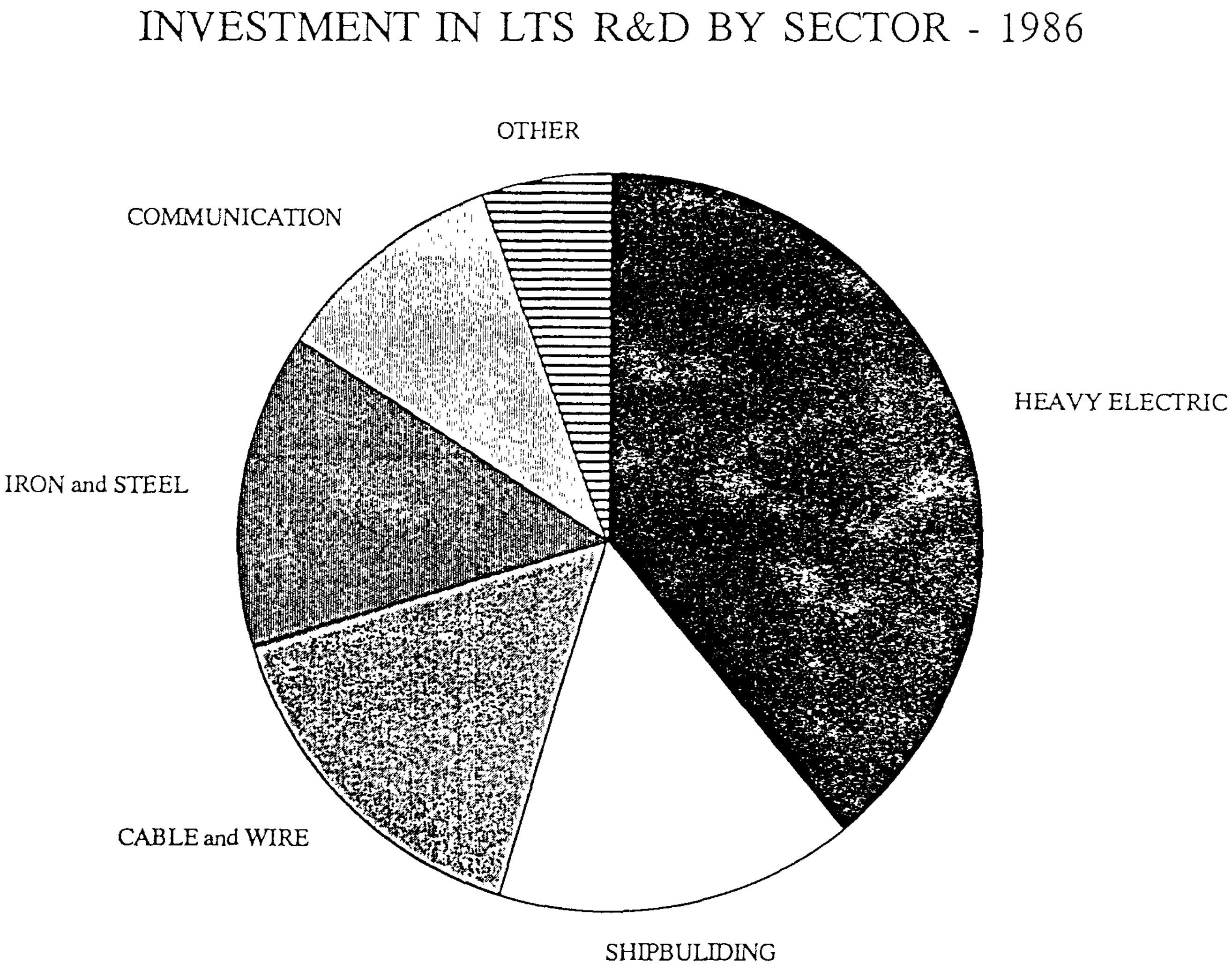
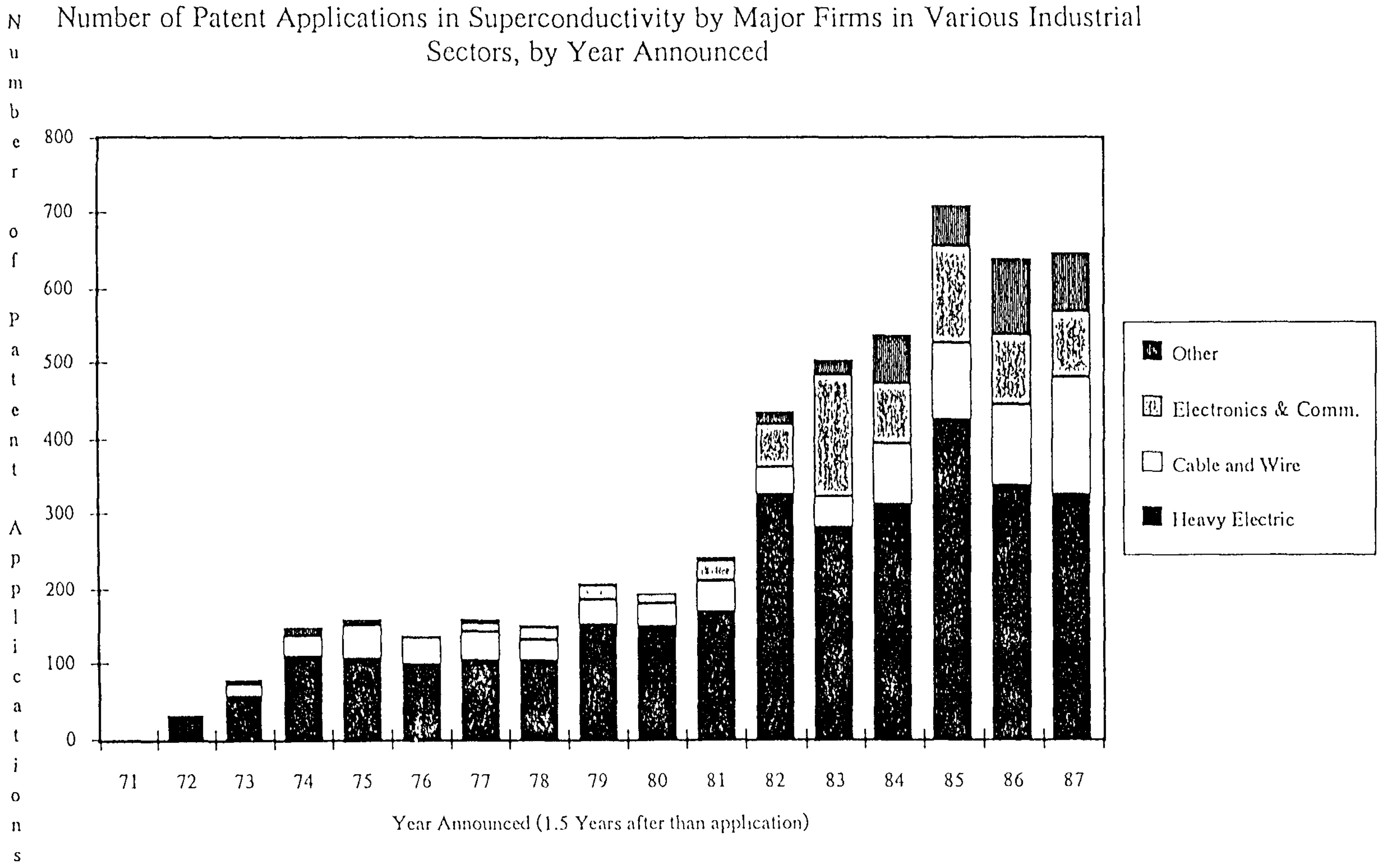


Figure 17. Sectoral Distribution of Activity in LTS Research Reflected in Patent Applications



# V. THE RESPONSE TO THE DISCOVERY OF HIGH TEMPERATURE SUPERCONDUCTIVITY

Upon the discovery of high temperature superconductivity, the Japanese government moved "at the speed of light." Or did they? In this section I will review the response of the private sector and the government to the discovery of HTS in an attempt to show how policy unfolded and what effect the government "lead" had in the overall response in R&D to this new opportunity.

Bednorz and Meuller published their discovery of higher temperature superconductivity in the September edition of the German journal, Zeitschrift fur Physik. What they observed was what appeared to be superconductivity occurring at a transition temperature of 30 K, which was 7 K higher than the existing record of 23 K achieved through NiGe. However, the data depicting the transition temperature were not entirely clean and they had not yet demonstrated the Meissner Effect.[65]

The discovery thus awaited confirmation and months passed without noticeable flurry in the scientific community. The news made its way to Prof. Shoji Tanaka's laboratory at the University of Tokyo several months later, in August, thanks to the careful eye of Prof. Kazuko Sekizawa at Nihon University.[66] She had been conducting research into the possibility of superconductivity occurring in just such a perovskite material, and realizing the potential significance of the IBM work, quickly passed the news on to her colleagues by phone. She called Prof. Kitazawa, also of the University of Tokyo, who quickly shared the information with Prof. Tanaka. The Kitazawa and Tanaka laboratories then geared up and focussed the work of their research teams on the task of confirming the higher temperature superconductivity.

On November 28, Prof. Tanaka announced his confirmation of higher temperature superconductivity in a ceramic material in an article in the Asahi Shimbun (Newspaper).[67] In the article he noted that they had verified the Meissner Effect with the Lanthium-Barium,

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[65] A widely circulated view that has developed since then was that Bednorz and Meuller purposely published in a less circulated German journal rather than an international publication so that they could both lay a claim on the discovery as well as buy themselves time to confirm what they think that they have found. Science here does not seem to be free of competition.

[66] Rumors have circulated that the information came from a fortuitous visit of a Japanese researcher to IBM, but this is disputed in Japan. In October, Prof. Masake Takashige from the University of Tokyo was visiting the IBM Zurich laboratory and there learned directly about the experiments. While this provided confirmation of the work underway, it appears not to have been "the event" which sparked labs in Japan.

[67] "Chodendo no ShinZairyo wo Hakken - 'Koon' demo jubun na ugoki," Asahi Shimbun, November 28, 1986, p.3.

Copper-Oxide material described by the IBM researchers. However in reality, the data were still less than perfect, and Prof. Tanaka and his students were working long hours to produce a clean graph.

Then came the annual winter meeting of the Materials Research Society in Boston in early December. On Wednesday, December 3, Prof. Tanaka's laboratory finally produced clean data which verified the occurrence of the Meissner Effect with this new material, and the results were faxed to Prof. Kitazawa in Boston. On Thursday, December 4, during a session which included papers on some older oxide materials, Paul Chu gave a presentation at the end of which he announced the confirmation of the IBM findings. Prof. Kitazawa then presented the results that he had just received, and the high temperature superconductivity boom had begun.

How did the government and the private sector respond to the confirmation of this discovery? In brief, the private sector reacted very quickly, and the government, particularly MITI and the STA, very slowly in creating programs to support research in HTS. Examination of this response shows that even as the primary promoters of science and technology in the government, these bureaucracies are still bound by the procedures of the budgetary process, and these procedures are not designed to accommodate the quick support of new discoveries in science. In this instance, contrary to popular image, MITI was not the fastest but the slowest organization to react, lagging the initiatives of STA and MOE, and lagging the response of the industry which it is often envisioned as leading. The timing of these actions and the process through which formal government policies came to form will be described below.

### The Government Response

Contrary to its image as one of the government's slowest and most bureaucratic organizations, the Ministry of Education was the first to provide funds for HTS research as a result of Prof. Tanaka's confirmation. Within a couple of weeks, Prof. Tanaka, as well as several other of the professors involved in oxide materials research, found that the Ministry had transferred several million yen to their *koza* , money intended to allow the purchase new equipment for HTS experiments.

The Ministry's three year superconductivity research program was scheduled to conclude at the end of March 1987, but the Ministry responded to the HTS discovery with surprising decisiveness, continuing its support by extending the project for another year. 169 million yen was allocated through the Grant-in-Aid program with fifteen individuals selected and the themes narrowed to one, oxide superconductors.

The Science and Technology Agency was the next to create a program, forming the New Superconducting Materials Forum under the wing of one of its associations, The Society of Non-traditional Technology. The purpose of the forum was to serve as an information clearing house for new developments, domestically and internationally, in this field. The first meeting was held on February 26, 1987, just ten days after Paul Chu had announced at a press conference of a material which appeared to superconduct at temperatures above that of liquid nitrogen. For many in attendance, this was the first occasion to hear about the breakthrough, giving the forum a very positive start. Within a month membership had grown to 60 firms.

During the January to February period, plans for programs to support research in HTS materials began to float up through the ranks of STA and MITI, but these plans would take more time to unfold.

The next move made in policy circles was by politicians in the National Diet. In February, small study group, a *"kondankai,"* was formed in the Liberal Democratic Party, led by Takashi Tawara, a civil engineering graduate of Kyushu University and a person who was at the time the Director of the Lower House Committee on Commerce and Industry, *"Shugiin Join Iinkai,"* and who had been the parliamentary Vice Minister to MITI.

On April 16, 1987, nineteen members of the Liberal Democratic Party announced the formation of an association formed to support government involvement in superconductivity, the *"Chodendo Sangyo Giin Renmei."* The *Renmei* was chaired by Seiryoku Kajiyama, a senior member of the Takeshita faction, who was Chairman of the Lower House Committee on Commerce and Industry and was later to become Home Minister and Deputy-Secretary General of the Party.

The stated goals of the *Renmei* were the following.

- Assuring the allocation of funds for the promotion of the R&D and development of industrial applications of superconductivity.
- Acquiring experimental equipment and research facilities needed for the development of industrial superconducting technologies.
- Promoting policies for the education of personnel needed for the development of industrial superconducting technologies.[68]

The effect of the Renmei in policy-making will be discussed in the following section.

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[68] Chodendo Sangyo Giin Renmei, "Shuisho," April 16, 1987.

The STA formally announced its plans to support a R&D program in superconductivity, on September 21, 1987, when the Research and Development Division of the Science and Technology Agency released its report *"Chodendo Zairyo Kenkyu Kaihatsu no Aratana Tenkai,"* (A New Stage in the Research and Development of Superconducting Materials).[69] Here STA described its plan to develop a "Multi-Core Program," which centered around a set of STA laboratory facilities, each responsible for a different priority research theme. The strategy was thus drawn, but there was no funding to move quickly into action. The start of the Multi-Core Program would have to wait for the beginning of the following fiscal year, in April of 1988.

The first overall statement of policy toward HTS from the government was not announced until November of 1987. The Council for Science and Technology through its Policy Advisory Committee approved the release of a statement drawn up by a special committee set up to consider policy toward HTS, the *"Chodendo Ni Kansuru Kondankai"* (Superconductivity Discussion Group), in their report *"Chodendo Kenkyu Kaihatsu no Kihonteki Suikhin Hosaku ni Tuite,"* (A Basic Policy for the Promotion of Research and Development in Superconductivity),[70] they noted the potential for the continuing rapid advance of this field and the importance of thus moving expeditiously. The report made general statements for the increased support of research funding, researcher training, basic research facilities, and the exchange of information.

Finally, in December, MITI, through the report of its own discussion group, the *"Chodendo Sangyo Gijutsu Kaihatsu Kondankai,"* announced that it would establish a joint research center for the exploration of HTS, with funding to be provided by both the government and the private sector participants.

On January 14, 1988, the International Superconductivity Technology Consortia (ISTEC) held its inaugural ceremony at the Imperial Hotel in Tokyo and a week later, on January 21, was formally registered as a non-profit organization with the government. The office for its administrative section was opened in the Shimbashi section of Tokyo.

Laboratory work, however, was not to start until July when the Nagoya laboratory, which focussed on research in high current properties, began operation. The main research center, in Shinanomachi on the outskirts of Tokyo formally began operation on October 25, 1988.

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[69] Kagaku Gijutsucho Kenkyu Kaihatsu Kyoku, "Chodendo Zairyo Kenkyu Kaihatsu no Aratana Tenkai," Kagaku Gijutsucho Kenkyu Kaihatsu Kyoku: Tokyo, September 21, 1987.

[70] Kagaku Gijutsu Kaigi, "Choudendo Kenkyu Kaihatsu no Kihonteki Suishin Hosaku ni Tuite," Kagaku Gijutsu Kaigi: Tokyo, November 1987.

With the beginning of the new fiscal year in April of 1988, the Ministry of Education began a new three-year program in superconductivity, this time focussing on oxide materials. The program involved 19 principal research tasks under three themes, fundamental structural analysis, new electronics, and oxides and chemical composition.

The Science and Technology Agency also began its operation of the Multi-Core program by beginning the distribution of funds to each of its "core" research facilities.

### The Industrial Response

With the government responding in forming policy and R&D programs as described above, one would then ask how this compares with the response in the private sector. Does government policy seem to lead or lag the activities of the private sector?

All of the firms engaged in superconductivity research at the time of the discovery reported that they initiated research into oxide superconductors within days, and in some cases before the December announcement. The attempts by the Tanaka and Kitazawa laboratories to confirm the IBM discovery was known by many of these firms, and the more adventurous, notably Hitachi and Sumitomo Electric, began similar research in their own laboratories on a small scale in the fall of 1986.

One of the appealing characteristics of this new material was that little new capital investment was needed to get started its research. Thus firms not yet involved in superconductivity did not face major investment barriers in entering this new field, and many firms in related materials industries such as glass, ceramics, steel, and metal alloys began assigning researchers to monitor the developments and begin exploratory research. The major organizational moves, however, occurred in the established firms.

In February, Matsushita created a similar inter-laboratory project team to explore superconducting materials and devices. With a number of research facilities and affiliated research facilities spread around the Osaka area, and with research teams expert in communication devices located in Yokohama, the function of the project was to provide administrative and financial support to allow the laboratories to share expertise and information about new developments.

One of the first major organizational commitment was made by Hitachi, in March, when it formed a formal three-year inter-laboratory project in superconductivity. Known as a *"tokken"* project, it involved new funds for equipment purchase and more importantly the sharing of expertise among 60 researchers from 12 different laboratories and three production divisions. Hitachi laboratories participating included the Central Research Laboratory, Hitachi Research, Hitachi Cable, Hitachi Chemical, the Mechanical

Engineering Laboratory, the Energy Laboratory, the Product Engineering Laboratory, and the Advanced Research Laboratory. In addition, researchers from the Rinkai Branch, Naka Branch, and Main Branch of Hitachi, Ltd., also participated.

Also in March, a 30 researchers at NEC had formed an informal project team cutting across departments to investigate HTS materials. Formed under their PF-II (Project Fundamental II) system, it allowed researchers to organize for independent research without special reporting requirements to or aid from the company. At Sumitomo Electric, a Superconductivity R&D Group was formed, and in April Toshiba initiated a special project to in HTS and Ishikawajima-Harima (IHI) formed a HTS project team.

By the middle of the year, a large number of companies has formed groups to pursue research in HTS. In June, Fuji Electric formed a HTS research team at its Basic Research Laboratory, drawing on researchers from a number of different departments, and in the same month at Fujitsu, superconductivity research at their Central Research Laboratory was reorganized into three new groups all of which included HTS: 1) Materials R&D, 2) Semiconductor Crystal Growth (Thin Films), and 3) Josephson Junctions and Electronic Devices. Other firms forming superconductivity R&D teams include Mitsubishi Electric, Kawasaki Steel, Mitsubishi Metals, and Showa Cable.

In September, Furukawa Electric formed a new Superconductivity Department at its Yokohama R&D Laboratory in an effort to collect in one laboratory the diversity of expertise they found necessary for the pursuit of HTS. Ceramicists, chemists, optical fiber specialists were placed together with researchers in metallic superconducting materials. At the same time, the other departments continued their HTS research, with the ceramics department, for example, having turned their attention almost entirely to superconducting materials. In October, Sanyo announced it had formed formal HTS research teams.

The following year saw a continuation of this trend toward reorganizing firm research to allow a mixing of expertise in HTS. In January 1988, Sumitomo Electric established a Superconductivity Department in its Osaka Laboratory, which took the lead for coordinating firm-wide HTS research with the work also underway at the Basic Technologies Laboratory, the Information and Electronic Technology Laboratory, the Itami Laboratory, and the Yokohama Laboratory. In March, the PF-II activity at NEC had been upgraded to a PF-I project, which meant that it would be recognized as a formal priority project of the firm and given special financial support. In additional to the funds, this also meant that there would be a greater level of stability in the ability of researchers to pursue this work. And, in April, Toshiba established a Basic Research Laboratory with half of the lab's 84 researchers assigned to materials development and device applications of HTS.

# Table 8. Timing of Policy and Private Sector Responses to the Discovery of High Temperature Superconductivity

| HTS Event | Date | Policy Event | Private Sector Event |
|---|---|---|---|
| | **1986** | | |
| Tanaka Announcement in Asahi Shimbun | **November 28** | | |
| Announcement at MRS Meeting | **December 4** | | |
| | **1987** | | |
| Chu Announcement of HTS above 77 K | **February 16** | | |
| | | | NEC - PF-II Team<br>Matsushita - Special Project Group |
| | | First Superconductivity Forum (STA) | |
| American Physical Society Meeting, "Woodstock of Physics" | **March** | | Hitachi - "Tokken" Project<br>Sumitomo Electric - Project Group |
| | **April** | | |
| | | MOE Extends Superconductivity R&D Program | Toshiba - Project Group<br>IHI - Project Team |
| | | LDP Discussion Group | |
| | **May** | | |
| | | | Mitsubishi Electric - |
| | | Project Team | |
| | **June** | | Fujitsu - 3 Project Groups<br>Fuji Electric - Project Team<br>Mitsubishi Metals - Project Team<br>Kawasaki Steel - Project Team |
| | **July** | | |
| | | | Showa Cable - Project |
| | | Group | |
| | **August** | Superconductivity Budget Proposals Submitted to MOF | |
| | **September** | | |
| | | Multi-Core Program Plan Announced | Furukawa - SC Department |
| | **October** | | |
| | | | Sanyo - SC Group |
| | **November** | Council for Science and Technology Announces Policy in Superconductivity | |
| | **December** | | |
| | | MITI Announces Formation of ISTEC | |

| HTS Event | Date | Policy Event | Private Sector Event |
|---|---|---|---|
| | **1988** | | |
| NRIM Announcement of Bismuth Alloy HTS at 110 K | **January** | ISTEC Inaugural Party | Sumitomo Electric - SC Department |
| Univ. of Arkansas Announcement of Thalium Alloy HTS at 125 K | **February** | | |
| | **March** | ISTEC Office Opens | |
| | **April** | MOE Begins 3-Year Program in Oxide Superconductors<br>Multi-Core Program Begins | Toshiba - Basic Research Lab |
| | **May** | | |
| | **June** | | |
| | **July** | ISTEC Nagoya Laboratory Opens | |
| | **August** | | |
| | **September** | | |
| | **October** | ISTEC Main Laboratory Opens | |
| | **November** | | |
| | **December** | | |
| | **1989** | | |
| | **January** | | Fujikura - SC Department |
| | **February** | | |
| | **March** | | Hitachi Research - SC Center |

Continuing into 1989, in January Fujikura Cable created a Superconductivity Technology Department in recognition of internal growth in staff that had occurred over the past two years, and in March, Hitachi Research reorganized its superconductivity R&D under one roof and announced the formation of a new Superconductivity Research Center. These events are summarized in Table 8.

- *Questionnaire Data*

From my questionnaire data one can see that these was substantial diversification into superconductivity after the HTS discovery. Figure 18 compares the investment in superconductivity R&D in 1986 with that in 1989 by the firms surveyed in various sectors. Whereas the number of principal sectors were few and the Heavy Electric and Cable and Wire sectors were dominant in 1986, the situation was quite different in 1989 with many more sectors significantly involved. Separating the LTS and HTS activities as seen in Figure 19 confirms that the diversification is occurring in HTS research, with the traditional industries continuing to be strong in LTS.

Through this data and additional information about industrial activity overall taken from patent applications, the size of the industrial investment in superconductivity in 1989 was estimated at 19.4 billion yen. Of this amount, 34% was going to LTS and 66% going to HTS. This overall amount is 60% higher than the 12.06 billion yen estimated for 1988 by the U.S. Office of Technology Assessment.[71] These estimates are shown in Figure 20.

### Analyzing the Government Response

One point which becomes clear from the description of public and private sector responses to HTS was that the private sector was much quicker to respond in supporting research than were the bureaucracies. Neither did MITI move at the "speed of light"[72] nor did it even lead the private sector in the year following this discovery:[73] MITI lagged. The firms moved quickly and on their own. MITI, in fact, was the slowest of the three

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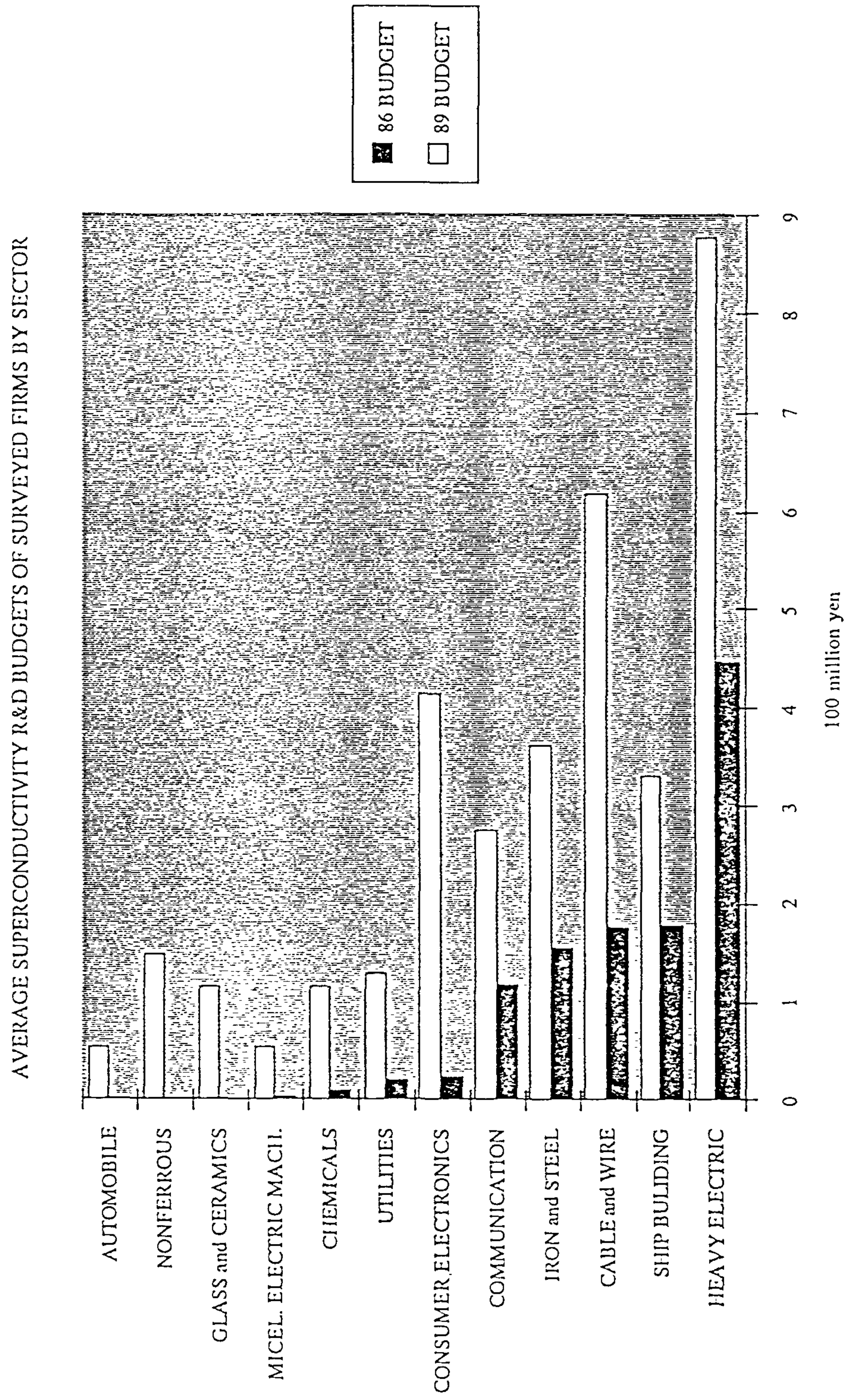
[71] Office of Technology Assessment, High-Temperature Superconductivity in Perspective, OTA-E-440, April 1990, p. 93.

[72] Michael Crow, "Technology development in Japan and the United States: lessons from the high-temperature superconductivity race," Science and Public Policy, Vol. 16, No. 6, December 1989.

[73] 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." Japan Technology

Figure 18 Investment in Superconductivity in 1986 and 1989 by Sector - Among Surveyed Firms



Evaluation Center, JTEC Panel Report on High Temperature Superconductivity in Japan, Washington: NTIS, November 1989, p.4.

**Figure 19** Investment in LTS vs. HTS in 1989 - Among Surveyed Firms

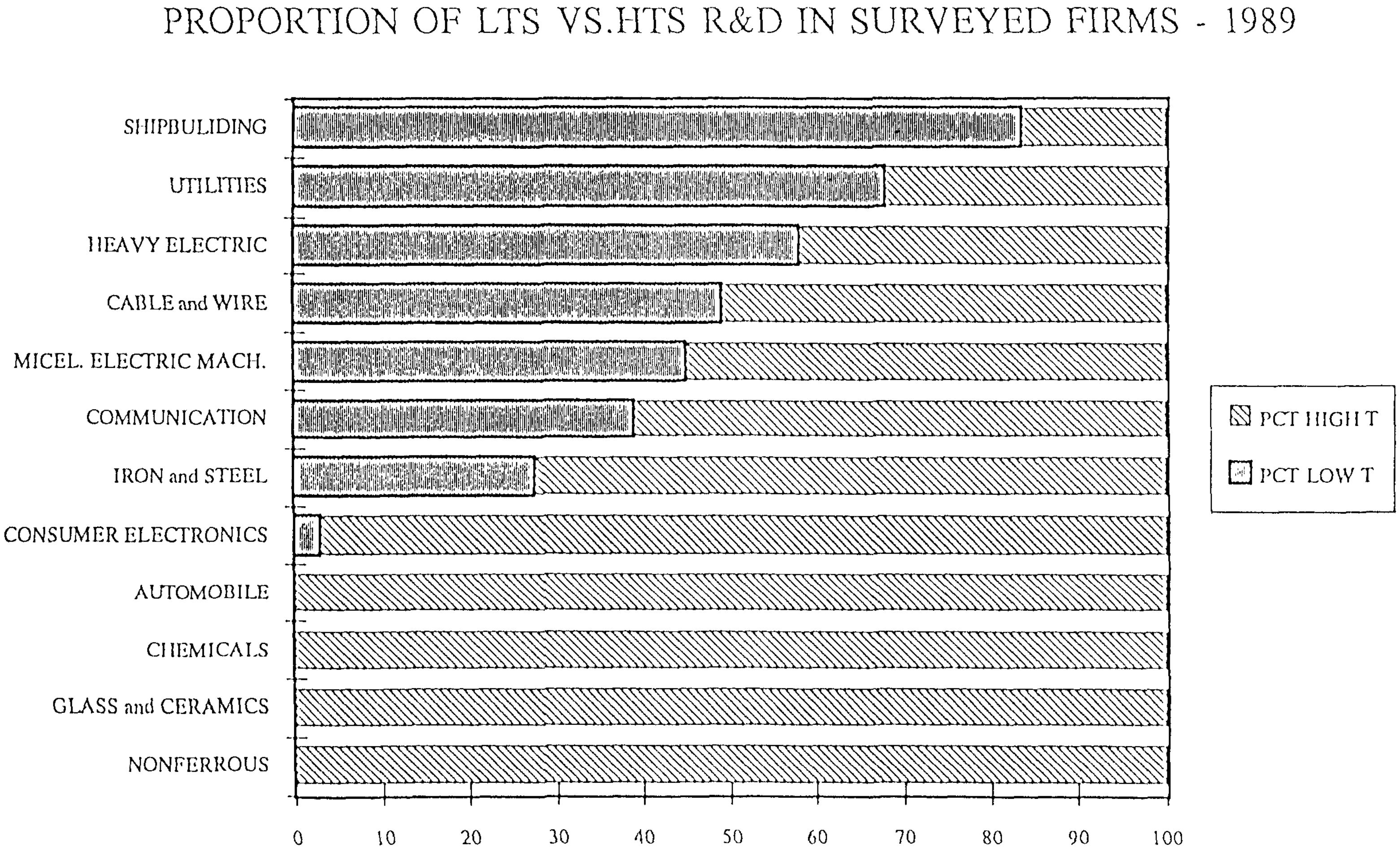
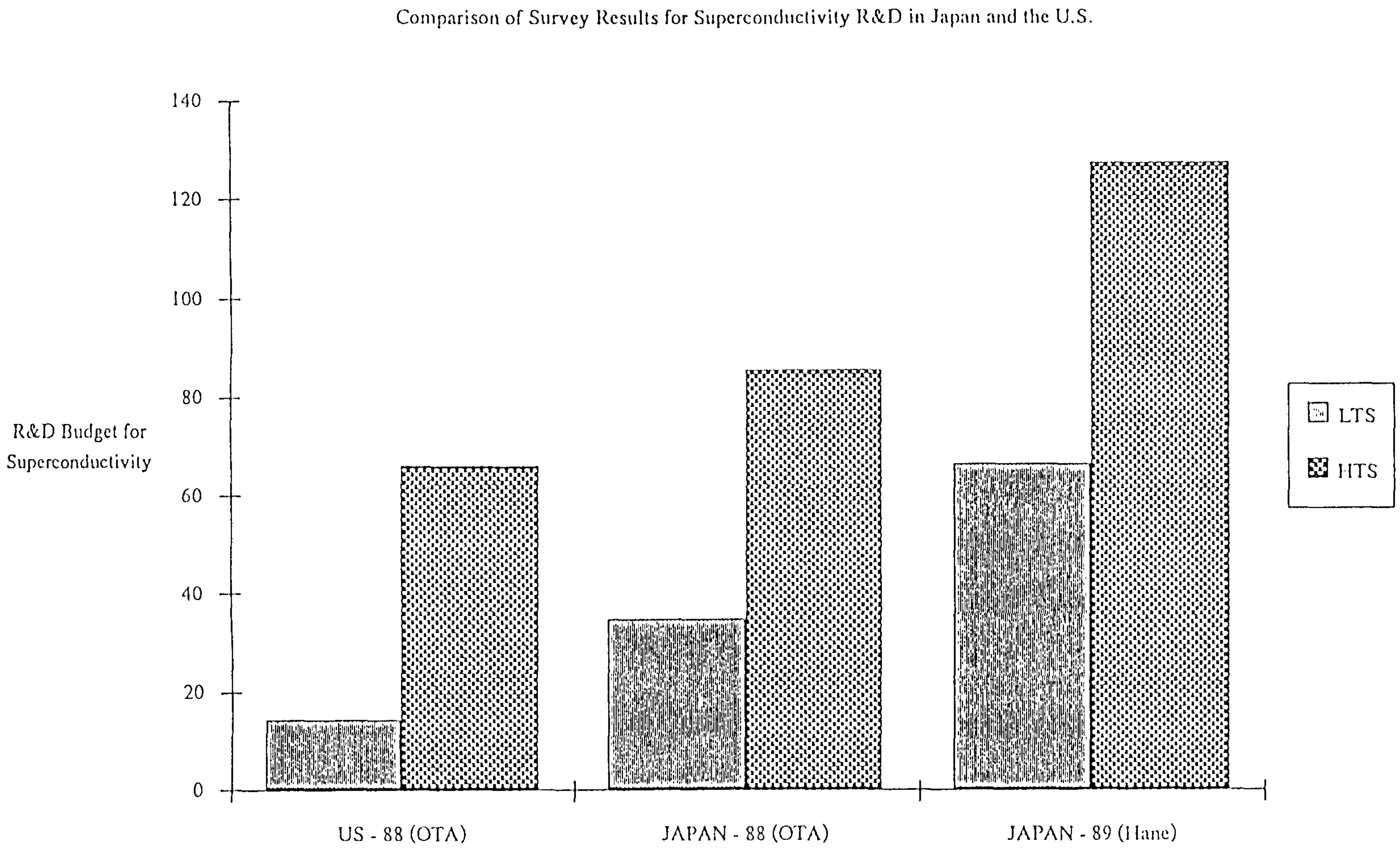


Figure 20 Comparison of Estimates of Industrial Funding of Superconductivity R&D



bureaucracies to move. How this came about and how policy was settled generally will be described later in this chapter.

The breakthrough in HTC did not occur at an opportune time in the government's budgeting process. The end of December marks the deadline for defining all budgets that will be submitted to the Diet for the following fiscal year beginning in April. Throughout December, staff in the Ministry of Finance work frenetic, nearly around the clock hours to settle all of the accounting details, and the last thing that they want to hear is that ministries need more money to explore a new scientific phenomenon. Thus the R&D supporting ministries and agencies were confronted with several challenges: 1) to quickly find a way to advance this new phenomenon, 2) to do so in a way that would distinguish their research from competing ministries and agencies, and 3) to do so in a way that could circumvent the lack of new near-term funding from the Ministry of Finance.

### - *Ministry of Education*

As mentioned earlier, the Ministry of Education was the first of the bureaucracies to respond in research support. How did this happen? The key to the MOE response are organizational and lies in 1) the power given to Professors who advise, actually control, the research programs, and 2) the flexibility and shorter decision times needed in their system of distributing research funds.

In late November, the Ministry of Education was nearing the end of a three-year research program in search of new superconductors, and had little progress to show. They were thus highly pleased that Prof. Tanaka had saved the Ministry from having to report that it had no new discoveries, and eager to capitalize on its role in supporting the confirmation of HTS, the Ministry was willing to be moved quickly.

Because the headquarters staff of the Ministry of Education is not staffed with individuals who have scientific or engineering backgrounds, they have come to rely heavily on a network of advisory committees of Professors who formulate the actual research policy. The Ministry wields its power through its gate keeper function over the research budget and its nod of the head to the committee members' decisions.

The Chairman of the advisory committee to the superconductivity project, Prof. Nakajima, quickly moved to allocate the remaining equipment funds in the project to the laboratories conducting research in inorganic superconducting materials. As a result, Prof. Tanaka and others in this area, received the timely bonus to their "koza."

Adding to the flexibility in the decision-making process is the shorter lead time required for applying for and then creating new programs in the MOE. In the Grant-in-Aid for Scientific Research Program, there is a special fund known as the *"Tokubetsu Kenkyu Sokushinhi,"* (Special Research Promotion Fund) which has been set up to respond to this type of unexpected development in science, as well as unexpected political demands of science. The researchers were thus able to scratch together a quick proposal for a one year extension that would allow continued work in these new oxide materials. This allowed for a preservation of some research momentum while a plan for a larger, more comprehensive research program could work its way through the normal funding system.

One must also recognize a certain amount of serendipity in the timing of the science and the research program. Had there not been an existing program, mobilizing a network of researchers would not have been as readily accomplished. Researchers could share information about world wide developments in this new field at their already planned third annual symposium of the superconductivity project held on January 19, 1987.

### - *The Science and Technology Agency*

In the Science and Technology Agency, bureaucrats gathered in informal groups soon after Tanaka's announcement to discuss program options. Unlike the MOE, the STA headquarters staff is composed of individuals with science backgrounds who themselves continually consider new research programs to create. Therefore these bureaucrats and their counterparts in STA's national laboratories took the lead in developing a research role for the Agency. Key to their strategy was finding a way of creating a program quickly to protect their claimed role in the support of advanced research from usurpation by MITI.

During the autumn of 1986, discussions were already underway within STA about creating a forum that would promote commercial interest in some of the recent LTS work of one of its laboratories. NRIM had developed a number of novel methods of processing metallic superconductors and several bureaucrats in STA felt that an effective means of diffusing this knowledge would be through the creation of an organization to disseminate the results, modeled after the successful experience of the New Diamond Forum.

The New Diamond Forum, established in July of 1985, was created to promote diamond materials and processing techniques developed at the National Research Institute for Inorganic Metals (NIRIM) as well as to be a general clearinghouse of information about worldwide developments in diamond processing techniques.[74] NIRIM had developed diamond processing equipment that was capable of compressing raw materials such as SiC,

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[74] For a summary of the technical developments leading to the formation of the New Diamond Forum see Y. Goto, "Diamondo Gosei Gijutsu no Genjo to Shorai," and M. Kamo, "Mukizaishitsu Kenkyujo ni okeru Daiyamondo no Kiso Gosei," in New Diamond, Vol. 1, No. 1, 1985.

$Si_3N_4$, or $Al_2O_3$ into diamonds at the highest pressures achievable at that time in the world. The institute also developed microwave plasma CVD techniques for producing diamond films for IC packaging, high output transistors, light emitting diodes, and laser light emission. The forum began with 85 corporate members, and after five years has increased its membership to 113 organizations. It has developed a reputation for identifying quality information for a nominal subscription fee and was highly evaluated by its participants.

The discovery of HTS thus occurred just as bureaucrats in STA were planning to organize a forum for superconductivity. The excitement over the discovery of HTS gave the idea a big push as a low visibility idea was transformed into the flagship of STA's entry into the arena.

Speed in organizing to support the development of this new area was important for technological as well as for political reasons. For the science and technology, researchers around the world were pursuing this new phenomena, often with shifts working around the clock on new compositions and processing techniques. To be able to contribute at the frontier of this new field, STA would similarly have to act soon.

An even more pressing pressure, however, was the need to establish legitimacy for its role as a primary player in the promotion of this field. Both MOE and MITI had ongoing programs in superconductivity and a strong interest in claiming a position as the lead organization in the government. If STA, wanted a place in promoting this technology, it had to move swiftly to develop a base of support and to develop a program that would reinforce its jurisdiction and build up its strengths. Otherwise, the funding would go to MITI and MOE: time and strategy were important.

STA established a strong political footing through the quick recruitment of Dr. Shinroku Saito, former President of the Tokyo Institute of Technology. Dr. Saito possessed a very strong reputation as a program head in both the academic and industrial circles, and his presence as head of the STA activity was seen to provide critical legitimacy for the agency's advance into this area. As Director of the New Diamond Forum, he was also familiar with STA's strategy. In early January, STA enlisted Dr. Saito to serve as the principal advisor and chairman of the forum. Later, MITI also approached Dr. Saito about taking a leading role in their program, but the commitment had already been made and the bureaucracies do not like having their leaders working on both sides of the fence. With Dr. Saito agreeing to be Chairman of such as Forum, STA had won an important first step.

Although the creation of an information forum was a fast and productive route for STA to claim its role in this area, it was still not research. As STA is charged with promoting fundamental research and as its laboratories had a long history in this technology, it seemed natural that it have a role in any government presence in this new field.

During January STA convened advisory meetings to discuss options for approaching this opportunity. Some in STA felt that this was such a significant discovery that it warranted a separate center for research. It was also known, however, that MITI was pursuing such an idea with the private sector, and that MITI's well integrated relationship with the industry would likely yield them more success than STA, should STA attempted a similar strategy.

Dr. Saito recognized STA's relative weakness if it adopted this strategy and also pointed out that the establishment of such a center would surely take time. STA's advantage would lie in speed and in the existing research capabilities of its laboratories. He thus suggested that existing facilities be exploited and enhanced, with each forming specialty centers with unique capabilities that would conduct research in collaboration with the industry and universities. This idea became the centerpiece of the research program that STA was about to create.

Dr. Saito's idea was welcomed by the STA laboratories as it meant that resources would not be funnelled to a new facility, which might further deprive existing activities of funds. Instead of reducing resources, the project would provide a significant inflow of new capital for these existing research groups. Politically, it was thus an easy idea to sell within the agency. During these discussions over program strategy, the locations and technical themes of the centers were also decided and the name Multi-Core Research Project was formalized in the middle of June.

The formal start of the Multi-Core Project, however, was more than a year away. A new allocation from the MOF could not be expected until the following fiscal year, which would start in April of 1988. This left abundant time for the planning committee to draw up a proposal for inclusion in the budget cycle that would begin in August, but research was taking off elsewhere in Japan and abroad. Even as Japan's principal bureaucracy charged with supporting frontier areas of science and technology, the agency had virtually no mechanism to obtain new funds to support the discovery. Means of providing for exciting new discoveries in science are not part of the Ministry of Finance's menu, and sympathetic ears were not to be found.

Without the ability to obtain new funds, STA was left with the option of reallocating funds from other projects under their jurisdiction. But within the agency, each budget item has its own agency constituency, with its own rationale of importance, and its own feeling of being underfunded. As pointed out by Tanaka and Hirasawa,[75] unlike decision-making in comparable bureaucracies in the United States, decisions in Japanese bureaucracies are made in negotiations between section chiefs. Decisions are seldom dictated from above. Although the General Coordination Office of STA is charged with oversight, its job is much more coordination than policy decision. In the absence of a decision-making authority, however, changes such as budget reallocation can be stalemated, and this is what seemed to happen in the case of HTS. No significant funds were reallocated by the STA.

Without new funds from either the Ministry of Finance or from the mother agency, it was left to the laboratories to find ways of supporting new research in this area. The only one of STA's laboratories to do so to a significant degree was the National Research Institute for Metals (NRIM). Here funds were reallocated rather quickly from the Director's discretionary research budget and from money received from STA's Special Coordination Funds for Promoting Science and Technology for a soon to be terminated project in superconductivity. From the Director's budget, approximately 10 million yen was allocated, and another 10 million yen was shifted from the ongoing project in conventional superconductivity to purchase some of the materials and equipment necessary to get started on HTS research.[76] At the National Research Institute for Inorganic Metals (NIRIM), which later cooperated with NRIM in the discovery and identification of the Bismuth based superconductors, no funds were formally reallocated.

Through the first half of calendar year 1987, the laboratories submitted and resubmitted research and budget proposals to the advisory committee and to STA. The advisory committee' primary role was to provide a technical review to confirm the priority of the areas identified, and to judge the fit of the research with activity at other laboratories. STA provided the administrative coordinative role for the various core and played the important but veiled role of communicating with MITI to guard against obvious redundancy in their projects. This precaution is less because MITI and STA wish for harmony between their programs, they would be happy to usurp the other's position, but because they know that they face the budgetary knives of MOF. Although MOF bureaucrats do not have the technical depth to understand the research program in detail, they may still be smart enough to spot obvious duplication, and obvious duplication is anathema to MOF's accountants.

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[75] Y. Tanaka, T. Imagawa, and R. Hirasawa, "Decision-making in Japan's Science and Technology Policy," draft, 1990.

[76] These budget figures were reported in NSF Report Memorandum #122, New "Superconducting Materials Research at the National Research Institute for Metals (NRIM) in Tsukuba," May 18, 1987, and were confirmed in conversation with Dr. Maeda of NRIM.

### - *MITI*

Belying its reputation as a leader of the industry, MITI was the slowest to move and had to be pressed into action by interested parties. Once, prodded, however, MITI showed the strength of its invisible administrative hand, as it eventually convinced a large number of firms to make a substantial investment to support its entry into HTS.

At the time of the confirmation of high temperature superconductivity MITI had a number of projects that were underway or planned to develop and apply LTS technology. However this work was device and systems oriented, relying largely on existing LTC materials. Examples include the superconducting electric generator projects, the Josephson junction element of the supercomputer project, and the discussion over developing superconducting magnetic energy storage prototype systems. Although each of these projects could incorporate HTS, none were appropriate for a broad-based development of the technology.

By the end of December 1986, there was still little sign that MITI was intending to do anything about the promotion of this discovery, perhaps thinking that it still belonged in the universities and national laboratories.

The period between the end of December and the beginning of January is Japan's largest national holiday season, "*Shogatsu*," the celebration of the New Year. City people traditionally use this time to return to their "*furusato*," their parents' or grandparents' home towns to take part in the New Year's feast, *"osechiryori,"* pay respects at the local shrine, *"hatsumode,"* and conduct the obligatory relative visits. It's one of the few times of the years when the trains in Tokyo are not crowded and when the majority of companies and stores close simultaneously. It's a holiday.

But research on high temperature superconductivity was accelerating around the world, including in many of Japan's universities and private laboratories. Convinced of the seminal significance of this discovery and convinced of the need for more substantial, coordinated support, Prof. Shoji Tanaka began the process of "*nemawashi*" to prod MITI into action. Prof. Tanaka had been involved as an advisor with several MITI R&D programs before including the famed VLSI program and the Optoelectonic Technology Program. He was familiar with both MITI's way of thinking and with many of the ministry's bureaucrats.

During the New Year's Holiday, Prof. Tanaka called one of his MITI acquaintances and said that he had an urgent matter to discuss. The MITI man visited Prof. Tanaka at his home and there Prof. Tanaka impressed upon the need for MITI to take action soon because 1) this was a field in which Japan was already at the international state-of-the-art, 2) a lack of action could cause Japan to fall further behind, and 3) if the temperatures continued to rise, this was a breakthrough with the potential of having a revolutionary impact across all industries and upon society internationally. This "*shogatsu*" meeting was the first step in setting the MITI machine in motion.

Toward the end of January, MITI organized its first advisory committee meeting on this phenomenon to discuss whether it should take any action. During the lunch break, Dr. Tsuneo Nakahara, Vice President for R&D at Sumitomo Electric Corporation asked Prof. Tanaka to accompany him for a quiet conversation. Dr. Nakahara had for many years been an ardent proponent of superconducting technology within the corporation. Although their research had been underway for many years with only marginal commercial return, Dr. Nakahara felt that only through commitment in the long-term would the investments yield the company benefits. The HTS discovery, he felt, added tremendously to the potential impact of this material.

Dr. Nakahara agreed with Prof. Tanaka that this was indeed an epochal breakthrough and recognized that sustained research support needed to be achieved. He asked Prof. Tanaka how he might help. Prof. Tanaka responded that because his research was demanding a lot of his time, he could not devote as much time as he wanted to building support for policy action. Dr. Nakahara offered his services to let MITI know that the private sector was also serious about the potential of this technology, and after this meeting had his junior staff contact their classmates and friends at MITI, impressing the importance of taking positive policy action. MITI was thus gradually nudged into action. The impetus to get MITI moving was external, not internal.

There was still the problem of a constrained government budget and at least a year's time before any new money at all could be appropriated. Thus even if MITI were to take quick action, it wasn't clear what they should do.

Aware that STA would leverage its formal role as the government organization responsible for advanced research, MITI carefully emphasized its authority over industrial activities and the potential importance of HTS to future industrial development. Speed in establishing a foothold was an issue, but more important was the lack of funds in the near future. MITI realized that a timely response would require private sector financing. If able to weigh-in exhibiting significant industrial interest, pushing STA aside would be a less difficult problem.

This is when the idea of a cooperative research center that would be initially endowed and staffed entirely by the private sector began to float to the top of the agenda. In all of MITI's Research Foundations and Research Associations, the practice of having the participating firms supply the endowment had been established as well as the practice of the firms providing the staff for these organizations. MITI would normally provide the funds to conduct all or part of the R&D. Thus it was suggested that a similar course be taken, with the laboratory initially established with private money, and with MITI promising funds for research in the following fiscal year. Locating, equipping, and organizing a laboratory would take some time in any case, so that this would be a productive way of dealing with the time lag before MITI funding could become available.

However, in the case of virtually all past associations, the endowment asked of firms was only enough for office operation, and the staffing requested was small in number and limited to office work. In the case of this research center, they would need much more than that. They would need a laboratory, rather expensive research equipment, and research staff from each of the participating firms. In addition, unlike the research associations, which had a limited number of participants focusing on defined technology goals, it was not clear how many would be participating in this center and what the goals or the products would be. For a significant effort, it was clear that significant participation would be necessary. Although some optimists were arguing for a staff of 200, a more achievable size of 100 researchers became the general target.

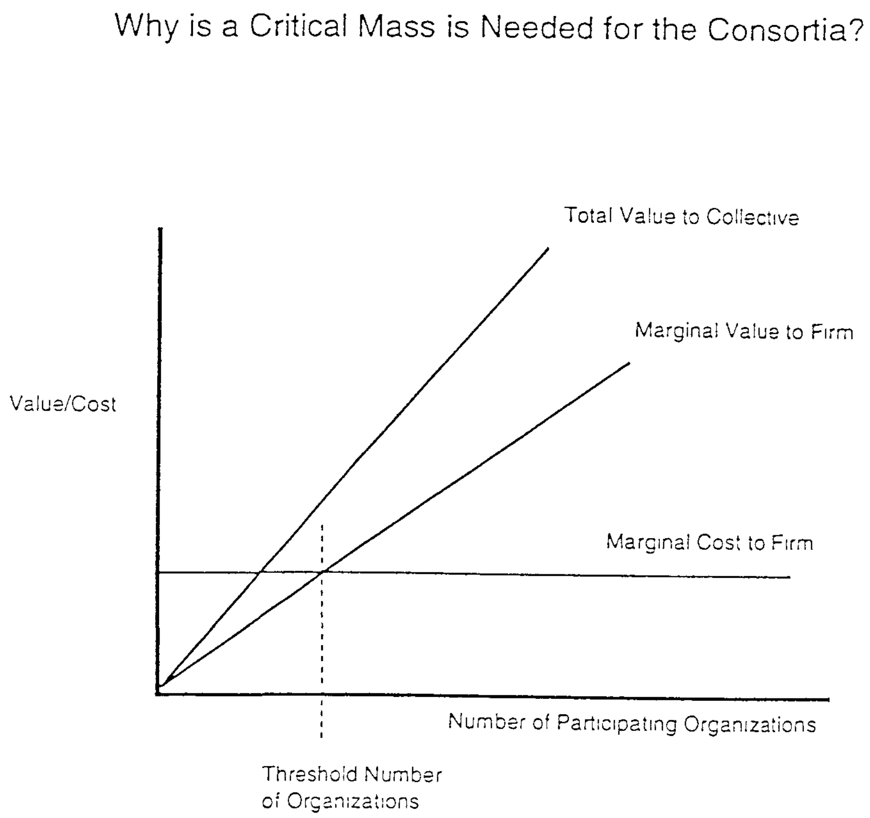
Firms that would be participating as full members would be asked to contribute 100 million yen to the endowment of the laboratory, to pay an annual fee of 12 million yen, and to contribute two researchers. This is a large investment for an unknown and largely unappropriable activity, so firms were hesitant and the approval of upper management took time.

But this is one reason that MITI exists, to cajole and to recruit commitment.

### - *MITI's Strategy of Recruitment and Administrative Guidance*

As a key step in developing the research center for ISTEC, one of MITI's primary challenges was in recruiting a critical mass of firms. A critical mass was necessary not just to achieve desired technical progress or to show a level of political support, but also to allow for formation of the laboratory.

Recall that in considering the decision to participate, a simple rational actor assumption holds that the firm would compare the probability of success multiplied by the magnitude of success with the probability of failure multiplied by the magnitude of failure. In a case such as HTS research, the calculation was very vague because of major uncertainties about the phenomenon and the speed of progress. However, the addition of



Why is a Critical Mass is Needed for the Consortia?

Figure 21. Cost/Benefit Curve Showing the Role of a Critical Mass of Participants in a Common Research Facility

contributors will more likely affect the potential positive outcomes more than the costs, as the costs are more fixed by the individual investment. This can be represented on the curve shown in Figure 22.

This curve, shows the marginal benefit to the firm, the marginal cost to the firm and the total benefit of the project, all as a function of the overall scale of the effort. The total benefit is assumed to be above the benefit to the firm, else the firms would have no incentive to participate. Participation is attractive to the firm when the level of operation is to the right of the intersection of the marginal firm benefit and marginal cost to firms, point A. However, as this is research with a significant level of uncertainty, the perception of where that intersection is may vary substantially. Thus the further to the right that the collective can place its operation, the more certain the firm can be that the cost/benefit approximation will be greater than one.

To serve the role of pushing this point to the right for ISTEC, MITI recruited all 10 of the nation's utilities and two utility research organizations. The utilities, however, are only prospective users of HTS systems, with likely use in the distant, not near, term. They are not materials developers or direct users of the material. So why did they join?

To understand this, the discussion will return to a description of the process of formation.

With the process set in motion by the advocacy of Prof. Tanaka and the lobbying of interested firms, the wheels began to turn in MITI to begin the process of establishing a center. But the initial move was not made by the arm in charge of promoting advanced research, the Agency of Industrial Science and Technology (AIST), but by the Agency for Energy and Natural Resources (ANRES).

The Deputy Director of ANRES and head of energy technology projects, Kunikazu Aisaka, had been trying to promote increased research in the utilities. He felt that the 0.6% of sales which utilities were contributing to R&D was too low a ratio and that the type of research performed needed to included more basic work to help offset criticisms of the utilities (and Japan) always being free riders. The discovery of HTS provided an opportunity to promote his more general goals.

Thus ANRES moved to recruit organizations to participate in the research center that Prof. Tanaka was seeking. The agency used arguments about the long-term impact of the technology, as well as its informal influence, commonly known as administrative guidance, to recruit all 10 of the utilities, 2 utility research organizations, 3 gas companies, and 5 cable and wire and systems manufacturers.

Important levers for administrative guidance which ANRES possessed were twofold. First is the "Koeki Jigyo," which provided ANRES with the authority to set rates for the utilities, much as a public utility commission would in the United States. Thus ANRES has the power to strongly affect the profits of the utilities as well as regulate their investments and sitings. The second tool is the special funds for research which come from a 0.2 percent tax on the utility sales. There are actually two such funds that are relevant, the "*Dengen Kaihatsu Sokushin Taisaku Tokubetsu Kaikei* (Special Promotion Funds for the Development of Electricity Generation)" and the "*Sekitan Narabi ni Sekiyu Oyobi Sekiyu Daitai Enerugi Taisaku Tokubetsu Kaikei* (Special Promotion Funds for the Development of Coal, Petroleum, and Non-Petroleum Energy Sources)." This money is distributed back to the utilities and to manufacturers for electric power research. When ANRES feels strongly about a policy measure which, in this case, would not significantly burden the utilities, the utilities are not in a position to turn a deaf ear.

Often in negotiations to gather a critical mass of participants one can observe the phenomena of tipping, sketched in Figure 23. Tipping occurs when one finds that there is a point in the recruitment process after which one finds that additional firms join readily.

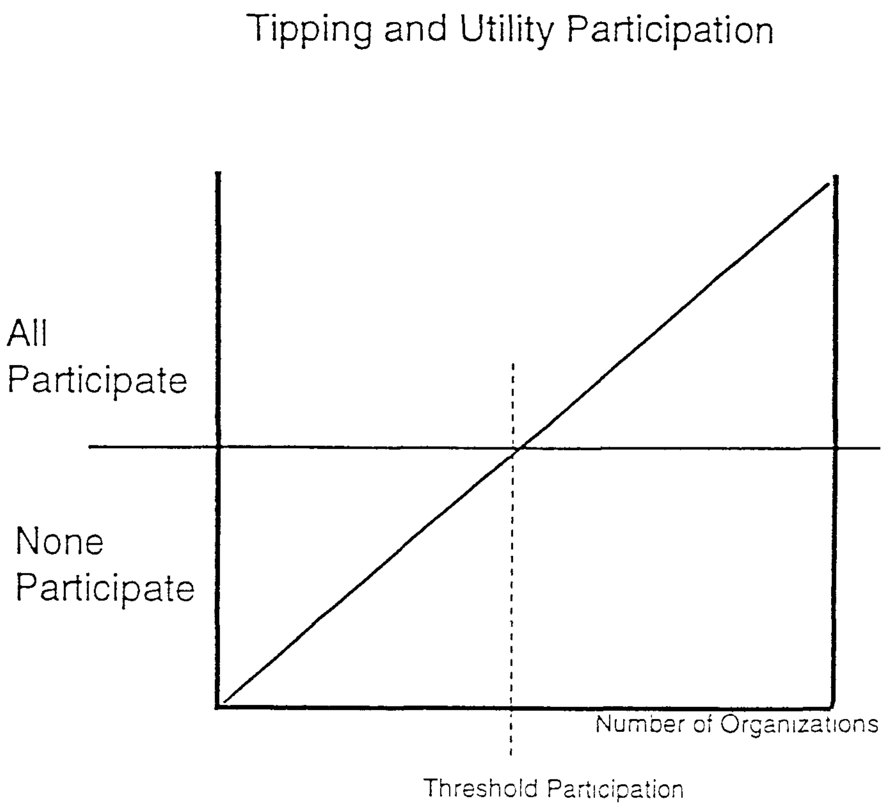


Figure 22. Tipping and the Recruitment of Utilities to ISTEC

Before this point, the firms are more hesitant to agree to participate because of the burden that would be borne if they were the only participants. But once an apparent critical mass has been achieved, recruitment is "tipped" and other firms join readily. Not joining brings the sigma of being perceived as a free rider and identified as an outsider by both the other utilities and the government regulator.

In this case it appears that although there was not significant hesitance from any of the utilities, tipping occurred after the big three utilities, Tokyo Electric, Kansai Electric, and Chubu Electric decided to join. With these three on board, the other utilities readily conceded to participation.

Here one might wonder why the utilities would not be more resistant given that they are users of the technology rather than users. Interviews indicated that the R&D managers in the utilities welcomed the intervention by MITI. The reason appears to be in their regulated status. Unlike manufacturers, the utilities do not have a strong incentive to aggressively promote research to remain competitive. Some research is needed to keep up with competition from alternative supplies, but the pressure is relatively low. However, all of the utilities have research centers or technical development groups and these individuals are eager to do state-of-the-art research. Thus they welcome the leverage provided by the intervention of MITI to leverage for more R&D funds internally. Rather than complain, it was commented that a number of R&D managers thanked MITI for the intervention.

Thus through ANRES, MITI was able to convince them to effectively act as a bank for the project. Although the funds are not a trivial amount for the utilities, the size of this investment in ISTEC pales, for example, when compared with the $30 billion in new capital equipment purchased in 1989.

Administrative Guidance also proved helpful in finding a location for the activity as the ANRES officials emphasized that they were not just interested in money but needed a location for the research. Several utilities and organizations offered sites for lease. These included the Tokyo Gas site, an unused power plant site in Shinagawa owned by Tokyo Electric, a site owned by Kansai Electric, and the Fine Ceramic Center (FCC) in the district of Chubu Electric. The sites out of Tokyo were not considered as attractive by the firms which indicated an interest in joining because many would have to relocate their researchers from their Tokyo based laboratories. In addition, the Kansai area was the site of the Super GM program so there was a feeling that they had enough salience in this technology. Chubu Electric and its area politicians pressed for some presence as it felt that its history in ceramics and the availability of the Fine Ceramics Center made it a logical candidate. But Nagoya was far from Tokyo. So a compromise was made with a branch facility assigned to the FCC and with the agreement that the first international conference hosted by ISTEC would be held in the Nagoya area.

Although the administrative guidance provided by ANRES was the strongest, they were not alone as AIST began to take a stronger interest in the project and eventually took over with the promise to increase the funding and the size of participation.

The details of the remainder of the consortia building process have yet to be opened for public analysis so it's difficult to know which carrots and sticks were offered in the process. The Japanese press has noted that the reluctancy of firms to commit the rather significant investment requested was a principal reason for the delay in beginning construction of the laboratory.[77] Other anecdotal evidence exists that not all firms were eager participants initially. Kent Bowen has commented that many of the electronics firms were resistant to this idea as they felt that their in house superconductivity R&D activity was adequate to address this new opportunity.[78]

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[77] "Chodendo Kogaku Kenkyujo ni Mukeru Kigyo no Netsui," Trigger, March 1988, Special Edition (Bessatsu), p.11.

[78] Kent Bowen, "Assessment of Japanese Research on High Tc Ceramic Superconductors," Working Paper, 1987.

It may be just as likely however, that electronics firms saw little immediate benefit from slightly higher temperature materials in their ongoing device research. The performance of Josephson Junctions in computers is a design and materials challenge that is not very sensitive to temperature. Thus the importance of committing funds to general HTS materials development may not have been seen as such high priority.[79]

To recruit additional firms for the activity a "consensus" was formed with other sections of MITI that this was an activity which the ministry as a whole should support, and so various arms of MITI were brought to bear. This is an important point because the Agency for Industrial Science and Technology is a technology promotion arm of MITI and as such has little direct coercive power over the industry generally. However other parts of MITI have regulatory and licensing functions which the industry needs for its current business and it was through these arms that pressures were applied. In addition to the Agency for Natural Resources, described above, there is the Industrial Machinery Division, which called upon some of the nation's major shipbuilders and industrial machinery manufacturers, the Automotive Division putting the call into auto makers, even through, again, they are not materials' developers. The Electrical Machinery and Consumer Electronics Division was called on to put pressure on the electronics and communications firms, and the Fine Ceramics Office to contact the ceramics and glass firms. These relationships are shown in Figure 23.

The organizers of this activity also well realized that developing political and public support for the activity would be important for longevity as well as formation. HTS research was not likely to yield commercial impact in the near future, so a broad base of visible interest would have to substitute for visible market return.

Thus through 1987 looked for other organizations from which it could draw support and resources. One category was organizations not involved in the superconductivity industry which were nonetheless willing to invest to both support and monitor an industry that could yield large future returns. These included six of Japan's major banks, eight construction firms, two trading houses, and an advertising firm. There were also firms which were involved in superconductivity only on a small scale, from the chemicals industry and transportation industries, and finally there were the non-MITI government organizations which because of their separate bureaucratic affiliations could not join as full members even through they were involved in similar research. There included

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[79] In addition, firms in general downplay the positive aspects of MITI projects to foreign visitors as a now common political strategy to avoid accusations of "unfair" government collusion, so it's difficult to know how much resistance was actually offered.

| Government Arm | | Industrial Sectors |
|---|---|---|
| Agency for Natural Resources | → → → | Utilities |
| Industrial Machinery Division | → → → | Shipbuilding, Industrial Machinery |
| Automobile Division | → → → → → → | Automobile Manufacturers |
| Electrical Machinery and Consumer Electronics Division | → → → → → | Electronics, Communications |
| Fine Ceramics Office | → → → → → → | Glass and Ceramics |

Figure 23. MITI Offices and Their Industrial Linkages to Recruit ISTEC Members

NTT, administered by the Ministry of Posts and Telecommunications, and the Railway Research Institute, administered by the Transportation Ministry.

To accommodate these firms, a second type of participation was created - regular membership. The regular members are given the right to receive publications and surveys and to attend center seminars, but are not party to the preferential licensing agreements given to full support members or to the know how developed in the laboratory. As not all such firms are comparably flush with cash, MITI also set up a two tier fee system. For firms listed on the first section of the Tokyo Stock Exchange or comparable size, an initial donation of 2 million yen was requested, with annual fees also of 2 million yen. For firms listed on the second section of the Tokyo Stock Exchange or of comparable size, an the initial donation was reduced to 1 million yen, and the annual fee to half a million yen.

MITI also used in influence in obtaining a home for the research center. Land anywhere near a metropolitan center in Japan is at a premium and the laboratory was also faced with the need to acquire very expensive experimental equipment to support its research. Thus discussions were carried out within the group of participants to search for an affordable leasing arrangement.

Outside of this group, politicians were also at work to influence the placement of the laboratory. This was, after all, to be a leading international center of research, and should breakthroughs occur which greatly expanded the use of this technology, industries would certainly be attracted to the location. A big effort to capture the location of the laboratory was put forth by politicians from the Nagoya-Gifu area. This area prides itself on its long history in ceramics, with it's industries producing 60% (check) of the nation's ceramic products. Several years earlier, in 1986, the provincial and city governments along with local industry and MITI had established a Fine Ceramics Center (FCC) for research into advanced ceramic materials. Since its founding the FCC had accumulated a broad range of state-of-the-art research tools, and half of the building space was still available for use.

The Tsukuba Science City area was also considered because of the greater availability of land and the proximity to the major government laboratories conducting HTS research. However the general feeling among the participants and MITI was that Tokyo was the preferred location because of its accessibility, its proximity to the business offices of many of the participants as well as to the government, and because Prof. Tanaka was living in Tokyo.

The land search was solved after MITI was able to successfully pressure another one of its regulated utilities to lease some of its land at a nominal charge to ISTEC. MITI persuaded Tokyo Gas to lease the site of its old managers' dormitory in the Koto Ward at the northeast end of Tokyo. This would be the cite of the main laboratory. As a compromise with the Nagoya contingent, it was agreed that a branch of the laboratory would be established at the Fine Ceramic Center. And it was agreed that the first International Superconducting Symposium to be sponsored by the consortium would be held in Nagoya at the end of August 1988.

It is also true that timing acted in MITI's favor. At the time of these discussions, the international "fever" in HTC was very much on the rise. Chu and Wu had made their discovery of 1-2-3 superconductors with a critical temperature of over 90 C, within a year later researchers at Japan's National Institute of Metals found Bismuth compounds superconducting at 108 K and Prof. Herrman's team at the University of Arkansas provided data on thalium compounds with a critical temperature of 120 C. There was no indication that the temperatures would not continue to rise, and the eventual goal of room temperature superconductivity was very much alive. As mentioned earlier, Nomura Research Institute based its market projections on the assumption of finding a room temperature superconducting material within 5 or 10 years. Many observers feel that subsidence of the fever soon after would have made this consortia impossible a year later.

In addition, Prof. Tanaka was retiring from the University of Tokyo. Mandatory retirement occurs at the age of 60 in Japan's public universities, and Prof. Tanaka was scheduled to retire in March of 1988. Perfect timing for the opening of the new center.

Thus MITI had the wave of optimistic projections to ride upon as well as the name of the nation's preeminent researcher in this new technology.

Thus with a combination of 44 full-support and 44 regular members the International Superconductivity Technology Center (ISTEC) was founded a great deal of fanfare on January 21, 1988. Approximately 600 people attended the opening party which was billed at 12 million yen, including the Vice Chairman of *Keidanren*, Hiraiwa Gaishi, the President of Hitachi Ltd., Mita Katsuhiro, and the President of Sumitomo Electric, Kawakami Tetsuro. The administrative office was opened in downtown Tokyo and a ground breaking ceremony was conducted on the Koto Ward, Shinonome site to begin construction of the laboratory.

As the Nagoya branch was able to use existing space in the FCC, it was able to begin operation rather quickly, on July 8,1988, less than a month after the branch head was recruited. Construction of the main laboratory at Shinonome meanwhile continued through the summer, through the "*obon*" holidays, and was finally completed in the fall, with the opening of the Superconductivity Research Laboratory (SRL) held on October 25, 1988. By the time of the opening, an additional 17 regular members had joined, bringing the total to 60. Thus one awakened, MITI showed that it could still flex its muscle with industry.

### - *The Ministry of Finance*

As the above discussion describes, important factor which drove the program strategies taken by STA and MITI was the 16 month waiting period before significant public funds could be directed to HTS research in April 1988. With the partial exception of the Ministry of Education, none of the Ministries or Agencies in the Japanese government has a system for the large-scale emergency funding of new scientific discoveries. Therefore they must appeal for additional funds from the Ministry of Finance and the Ministry of Finance has had little sympathy for pleas of unanticipated budget expansion.

Since 1982 the Ministry of Finance's top priority has been to reduce the spending deficit to zero, and then to reduce the national debt, which at 53% of GNP in 1989 is is about the same relative size as that of the United States. This priority has put a sharp edge on their budget scalpels, with science and technology no better protected than any other area of government service.

MOF determines an overall spending ceiling for each of the bureaucracies and it is up to the bureaucracies to stay within its allocation. How the funds are allocated are usually left largely to the discretion of the bureaucracies. MOF is not staffed with science or engineering graduates who would be able to challenge the technical substance of a program, and seldom does.

Interviews with individuals who were responsible for budgeting in the Ministry of Finance at the time, indicated that there was little excitement in MOF over high temperature superconductivity. The generally uniform response among these individuals was that there are many items on the budget list about which they must be concerned, with superconductivity being only one. The MOF is more concerned about controlling the overall size of the budget and checking for waste or redundancy, and less interested in or able to evaluate the technical potential of projects in science and technology. The technical decisions are left to the ministries and agencies to work out within and between themselves.

However, this also means MOF bureaucrats are not particularly inclined to favor developments in science and technology because of an inherent appreciation of the enterprise. If MITI or STA wanted to fund a HTS program in FY 1987, they would have to cut other programs, programs whose budgets were set as a result of their intra-agency history of year-long negotiations. Change, would be very difficult.

### The Funding Process

So the most practical option for MITI and STA was to abide by the normal budget process. The confirmation of HTS thus occurred at a very untimely point in the budget cycle.

Between January and June, the bureaucracies engaged in the planning of their research programs. Although the details are different between the ministries, the process is fundamentally the same. The section which would like to promote superconductivity draws up a plan and while doing so negotiates with the appropriate technology planning section to define the level of possible commitment. Since growth in the overall budget is minimal, trade-offs have to be made and funds taken from other activities. The negotiations are long, which explains the difficulty in starting new programs quickly.

Between June and the end of August, contact with MOF increases as the bureaucracies then fit their hopes to the budget guidance provided. The budget and program plan proposed has thus at least informally passed all major decision-making hurdles. The "*nemawashi*" results in a proposal that will closely resemble the approved plan.

It is in this stage of *nemawashi* that the influence of the Diet members, if there is to be one, is most likely to be helpful. Since there are no formal hearings which allow Diet members to press their opinions, they do so in informal visits to MOF. Managing Director of the Superconductivity *Renmei*, Takashi Tawara, noted that he visited the Ministry of Finance several times during the spring of 1987 to encourage their financial support of superconductivity. Very important to his influence, he noted, is the political standing of the members of the *Renmei*. The greater the standing, the more abiding MOF will be, at least ostensibly because the Diet has the final work on the use of the budget overall, and can create headaches for MOF if they have a reason to do so.

It is also well known that Diet members are influential in the *amakudari* posts of descending MOF officials, so the more influential the Diet member, the less that senior MOF bureaucrats are likely to want to ruffle his fur.

In addition to Kajiyama and Tawara, members of the Renmei are summarized in Table 3.9 along with some of the posts that they have held.

In addition to the individuals listed in the Table, there were eight Chief Secretaries. Among these, five were Parliamentary Vice Ministers of MITI.[80]

Evidence, however, of direct influence on the superconductivity budget forming process is unclear. In interviews with individuals at MOF who were at the time in charge of the MITI budget section, the STA budget section and the MOE budget section, it was strongly asserted that political pressure for a budget increase was not important in the case of HTS. In all cases these individuals had only vague recollection of Diet member visits to talk about this and other science and technology issues. All asserted that no special allocations were made to accommodate HTS. In fact, each of these MOF individuals had only vague recollection that superconductivity was an important event at that time (two and a half years had elapsed between this budget period and the time of the interviews.) Instead they emphasized their need to examine thousands of budget items for the bureaucracy with which they are charged, and the priority in keeping the overall figure within the MOF budget ceilings.

So a picture emerges with the research supporting organizations setting their agendas through in house bargaining, of a MOF which maintains a tight fist on the total amount of money used, and of a Diet which lurks in the background but is of little direct consequence.

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[80] These Chief Secretaries include Hideo Watanabe, Michihiko Shikano, Shozo Harada, Moto Shina, Kaoru Yosano, Shinji Sato, Isao Maeda, and Kanzo Tanigawa.

Table 3.9 Superconductivity Federation Membership List

| | | |
|---|---|---|
| Chairman | Seiroku Kajiyama | Chairman of the Lower House Committee on Commerce and Industry, Home Minister, and Deputy-Secretary General, LDP. |
| Advisor | Michio Watanabe | Minister of Finance, Minister of MITI, Minister of MAFF |
| Vice Chairmen | Mikio Okuda | Director of the Committee on Commerce and Industry |
| | Hikosaburo Okonogi | Minister of MITI and Deputy Secretary-General of the LDP |
| | Yoshiro Hayashi | Minister of Health and Welfare, Parliamentary Vice Minister of Finance |
| | Hiroyuki Masuoka | Deputy Secretary-General, LDP, Minister of Health and Welfare, Vice Minister of Transport |
| | Keijiro Murata | Deputy Secretary-General, LDP, Minister of MITI |
| | Kozo Watanabe | Parliamentary Vice Minister of Posts and Telecommunications, Chairman of the Lower House Committee on Communications |
| | Shigeru Kasuya | Deputy Secretary-General, LDP, Chairman of the Lower House Committee on Commerce and Industry |
| | Takeshi Noda | Deputy Chairman, LDP Policy Research Council, Parliamentary Vice Minister of MITI |

## Coordination

Finally there is the issue of coordination. With several bureaucracies moving forward to promote research in HTS and with each petitioning MOF for funds to support its plans, one might anticipate a role for scientific and financial coordinating bodies. Although STA has a nominal coordinating function in the arena of scientific activity, there is in practice little such role for it to play.

Formally, the behavior of the funding organizations would seem to confirm observations of general Japanese bureaucratic behavior made by a number of scholars, with each appearing to act largely independently of the other in drawing up its plans, working to maximize its relative position. However, this competition itself brings a certain amount of coordination, and the routes of inter-bureaucratic communication, while not formal, did allow for a high degree of information flow.

Although the bureaucrats face organizational barriers to formal inter-agency exchanges, professors do not. In the case of a scientific topic such as HTS, each ministry forms a scientific committee of professors for scientific guidance as well as for legitimacy in dealing with the Ministry of Finance and with the private sector. To head their respective advisory committees, each claimed a different professor. Prof. Nakajima, retired from Tokyo University and now at Tokai University, continued to chair the activities of the MOE; Prof. Shinroku Saito, previously President of Tokyo Institute of Technology was recruited by STA; and Prof. Shoji Tanaka became MITI's principal advisor. However, the community of professors identifies more with the science than with bureaucratic politics and communicates independently of the bureaucratic positioning. Thus through the mingling of the academics, each of the bureaucracies was well informed of the plans and activities of the other, and could develop strategies to emphasize different strengths and avoid conflicting in areas in which they were likely to lose.

Thus when STA learned that MITI was planning to form a research consortia that would be located at a single facility they abandoned their initial plan to create a similar activity. With MITI's far greater ability to recruit private sector participation, STA knew its position would be weak in trying to compete. So STA turned to the Multi-Core strategy. Overlap is guarded against through competition rather than purposeful planning.

At a general level, each ministry leveraged its ostensible mission and *de facto* strengths. For MITI, the mission emphasized was its role in aiding industry. Its strength was in its ability to work with industry and in leveraging the resources of the industry. For STA, the mission emphasized was its role in promoting areas of frontier R&D and its history in big science and technology projects. As it does not have the strong industrial ties that MITI enjoys, it emphasized its strength in its laboratories. One STA official commented that while MITI supports its projects to advance industry, in Multi-Core, STA was taking a strategy in which the industry supports the government laboratories and the science.[81]

However, the lack of a formal coordinating body means that each bureaucracy approaches MOF independently for research funds in the same area. With a high priority on budget control one might suspect that budget coordination would be an important issue. With three bureaucracies petitioning to do research on closely related if not clearly overlapping themes, one would expect coordinated scrutiny to occur.

But there is no formal coordination. Each budget section is matched to a specific ministry or agency, resulting in an insulated budget structure. No formal discussions or committees established to provide a comprehensive review of the research they were funding. Instead, each bureaucracy is asked how its program differs from the others', with little challenge to a reasonable rationale. Regarding the technical content, the technical bureaucracies are seldom challenged. MOF sets the ceiling for the agency or ministry and each is expected to live within its means.

### Conclusions

The discussion in this section reveals that far from "moving at the speed of light" in taking the lead in HTS research, the government bureaucracies, most notably MITI, lagged the response of the private sector in organizing research programs. Part of the reason was because as government agencies, they are bound by the funding procedures set by MOF, which are not designed to accommodate new discoveries in science. For MITI, the slowness was enhanced by the fact that they had to be prodded into action by interests in the private and academic sectors.

Once in place, however, the government programs for research are designed with the intention of sustaining investment in this area for a number of years, and as we will see in the following sections, sustained investment may be far more important than quick action.

The Diet was seen to have reacted rather promptly to the discovery of HTS, by forming an association for support, a *Renmei*. However the influence on policy-making, at least in this case, appears minor. Instead, the interest most served may be their own as the support of a cause that industry is interested in is clearly helpful in gaining political and

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[81] Interview with Shizuo Hoshiba, Director of the Office of Material Science and Technology.

financial support. Additionally, should HTS rise to room temperatures in the near future, as many thought likely then, it would have had a major impact on new commercial opportunities and on industrial growth. Being able to say that they were supporters from the uncertain outset would only enhance the level of appreciation that they could extract from industry

Finally, we saw that neither the Diet nor the scientific bureaucracies played any role in coordination. The actual technical content and level of commitment was left to intra-agency negotiations, within the overall caps set by MOF.

# VI. THE ORGANIZATION OF HTS RESEARCH CONSORTIA AND THEIR CONTRIBUTION TO INNOVATION

Having reviewed the formation of R&D projects to promote HTS, we now move to the questions of how these programs are organized and what contribution they have to innovation. In the analysis of the organization, the question of principal interest is how the interests of the collective accommodate the interests of the individual participants. Are conflicts significant in these consortia? How are the organizations affected in the areas of staffing, administration, and patterns of participation? The analysis of the organization will then be followed by an analysis of the contribution to innovation. Since the technical outcome of the research is still too distant to be understood the discussion will focus on a number of process characteristics. These characteristics include the contribution to the core science, diversification, diffusion, complementary assets, and training.

I will begin with an introduction to the technical organization of the ISTEC and Multi-Core Programs, discuss some of the tensions that exist and the resulting shape of the organization, and then examine of their contributions to innovation.

## The Organization of ISTEC and Multi-Core

### ISTEC

ISTEC'S technical goals are very general: to understand, advance, and to some extent develop technologies in high temperature superconductivity. There are no specific technical targets and no overriding research timetables, except for the initial 10-year period for the center's planned operation. Thus it is rather unlike other MITI promoted cooperative centers, such as the VLSI laboratory, ICOT, and the Key Technology Centers, which have all had technical goals and schedules against which progress was measured.

As described earlier in this chapter, uncertainty about advance is the salient characteristic of this field. There is uncertainty about the fundamental processes which allow this phenomena, uncertainty about what properties will lead to higher temperatures, and uncertainty about how easily these materials can be processed into usable forms and devices. It is these very uncertainties that enabled ISTEC to form as firms were being recruited to join when the only thing that seemed to be certain was that the field was advancing swiftly. Understanding ISTEC's organization and possible contribution to innovation thus begins with some understanding of the technical issues it is trying to address. We therefore begin with a technical introduction to the program.

ISTEC's SRL is divided into 7 research divisions focussing upon different research themes as shown in Table 10. Division I is charged with understanding the fundamental physics of superconductivity in new materials. Here the researchers are trying to understand the basic phenomena which provides for superconductivity in oxides, and to search for new tools to enhance their powers of characterization. The fundamental studies of physical properties emphasize four themes: 1) crystalline chemical properties, 2) electronic properties, 3) fluxoid properties, and 4) optical and surface electronic properties. In pursuing new characterization techniques researchers are examining the use of high pressure physics, pulse and specific heat measurement techniques for determining critical current and magnetic field, magneto-optical techniques of observing the fluxoid, and surface tunneling spectroscopy.

The Director of this Division, Dr. Koshizuka, commented that developing new characterization techniques such as those above is a high priority for his group.[82] He has noted, for example, that it is still very difficult to measure the critical current density of bulk materials. In general these are measured magnetically and indirectly characterized, not measured electrically. He also noted that at high critical currents, measurement becomes extremely difficult because of the heat that is generated.

Table 10 Organization of ISTEC's Laboratories

Superconductivity Research Laboratory

| | |
|---|---|
| Division I | Fundamental Properties |
| Division II | High Temperature Superconducting Oxides |
| Division III | Organic Superconductors |
| Division IV | Chemical Processing |
| Division V | Physical Processing (Thin Films) |
| Division VI | Data Bases |
| Nagoya Division | High-Current Superconducting Oxides |

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[82] "Looking Back and Looking Forward at SRL, "ISTEC Journal, Vol.2, No. 4, 1989, pp.8-9.

Division II focuses on the search for new ceramic superconductors. The improvements in critical temperature made during 1986 and 1987 were dramatic, but there is still a long distance to be crossed in the quest for the ultimate goal: to find a workable material approaching room temperature superconductivity. So Division II is charged with the task of searching for new superconducting ceramics, developing new HTS oxides, and analyzing, characterizing and modelling the materials. The search for new ceramics includes copper oxides, oxides not containing copper, as well as other ceramic materials. In analyzing and characterizing the materials the researchers are looking at electrical resistivity and magnetic susceptivity vs. temperature, Hall and thermoelectric effects, and, the composition and crystallographic structure.

Division III was created to address an entirely different type of material has exhibited superconductivity at low temperatures: organic superconductors. These materials are even less well understood than ceramics as their molecular structure tends to be far more complex than either metal or ceramic materials. In some ways they represent a field of dreams for superconductivity researchers because of a sense that their potential has only been scratched to date.[83] Prof. Tanaka has reflected this belief in this comment that "... high temperature superconductivity in organic materials presents a very unique phenomenon. I believe that a unique phenomenon occurs only in a unique material."[84]

Research in this division is addressing the development of organic superconductors and characterization of the physical and chemical properties of these materials, including their crystal structure, transport properties, magnetic properties, optical properties, isotope effects, and chemical properties.

Division IV focuses on the theme of chemical processing with the work divided into roughly four groups, depending upon the starting phase of the material: gaseous, melting or liquid, chemical solution, and solid. The head of this Division, Yuh Shiohara has commented that their first three years would be spent applying existing chemical and material fabrication processes to oxides to see which are most suitable. As the best methods depend on the product, Shiohara notes that a variety of such tools will be necessary. For example, with thin or thick films, CVD or sol-gel processing may be appropriate, whereas melt processing or solid phase processing would be used with bulk shapes.

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[83] Early in 1991, superconductivity was discovered in a pure carbon material, Carbon 60, which has the shape of a Buckminster Fuller Geodesic Dome. A group at Bell Laboratories initially announced achieving superconductivity with this material in April of 1991, with a critical temperature of 18 K. In July, a group at NEC in Japan announced increasing this temperature to 33 K.

[84] "Looking Back and Looking Forward at SRL," ISTEC Journal, Vol.2, No. 4, 1989, p.11.

By the autumn of 1989 Shiohara noted that all of his groups had succeeded in producing superconductors in the as-grown state. This groups have modified the Bridgman Method to produce Bi-system specimens with a Tc of 68 K, the Floating Zone process to produce a specimen with zero resistance at 80 K, MOVCD to produce Y and Bi-systems with a Tc over 80 K, and they have experimented with $O_2$HIP powder processing and sol-gel processing.

Division V is nominally chartered with the theme of physical processing, but the primary issue of concern is thin film research. The research is divided into two overall subthemes, the development of fabrication processes and the processing of superconducting oxide films into useful forms. The fabrication processes focus on thin films and on adapting semiconductor processing technology and decreasing the processing temperature. The processing of the films into useful forms includes fundamental studies on the physical properties of the interfaces between superconducting oxides and other materials, for possible multilayer capability, and exploiting lithographic techniques to optimize the conditions for milling of oxide films. The researchers employ equipment that includes a laser deposition apparatus, a multi-sputtering device, and a reactive evaporation apparatus for molecular beam epitaxy (MBE).

However, because of equipment delays, research has really only been underway since June of 1989. The Division Director, Tadataka Morishita, noted that in addition to the facility delays, they have also devoted time to redesigning some of the equipment ordered to suit anticipated experiments.[85] For example, much of this equipment was first developed for the semiconductor industry, in which an oxygen-free environment was essential. However, high temperature superconductors are oxides, and processing under higher oxygen environments appears to lead to better performance. So the equipment had to be revised to operate under high pressure oxygen environments rather than oxygen-free vacuums.

Division VI has been charged with developing a data base system, but as of late 1990 no full-time staff had been assigned and little progress had been made.

Finally, the Nagoya Division was given as their main theme high current superconductors. Although the theme allows for a broad range of research, the number of researchers was initially less than half that of the other sections, 6, so the Division Director, Izumi Hirabayashi noted that they decided it would be more effective to limit the number of topics addressed.[86] The main theme addressed in the initial months was the study of bulk

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[85] "Looking Back and Looking Forward at SRL," p.14.

[86] "A One-year Perspective on the Nagoya Research Division, SRL," ISTEC Journal, Vol.2, No. 3, 1989.

sintered materials.[87] In January of 1989 three more researchers joined the division and the work expanded to include the study of high-speed film fabrication via MOCVD. This work is being conducted in cooperation with similar research being carried out in Division 4. Other topics added to the scope of work at Nagoya include laser heated zone melting processes, thick film fabrication, and fundamental studies of the mechanisms limiting the critical currents in oxide superconductors. The variables that the researchers have focussed on include the characterization of raw materials, sintering behavior, control of directional ordering, control of the grain boundaries, introduction of pinning centers, and the use of composite materials.

### The Multi-Core Project

For STA, the Multi-Core Project represents a new organizational form and new organizational challenge. Although most of STA's R&D programs have been focussed on directly supporting research at its laboratories or through its public foundations, the agency showed in 1981 through the ERATO program, that it is capable of organizational innovations to meet the evolving needs of its science and technology policy priorities. Multi-Core represents a second major organizational innovation as STA is attempting to combine the resources of its laboratories and those of industry on a large scale to address a new area of science.

Like ISTEC, the Multi-Core Project has the very general overall goal of promoting basic research in new superconducting materials which will "pave the way" for their practical application.[88] The program is planned for 5 years, fiscal years 1988-1992, with STA providing the laboratory facilities which serve as the research centers or "cores," and providing funds to enhance existing equipment with the intention of enabling the cores to conduct frontier research. These cores are the heart of the Multi-Core project with each core focussing around a different technical theme. The core are staffed with researchers from the host facility, with these facilities also made available to researchers from other public and private sector organizations who submit proposals for collaborative research. The overall arrangement is shown graphically in Figure 24.

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[87] The first patent applied for by this Division, for example, involved the addition of silver during the processing of a 1-2-3 La-system superconductor. The silver was found to accelerate liquid phase sintering and thereby improve both the critical temperature and current of the superconductor.

[88] Science and Technology Agency, "Multi-Core Research Project on Superconductivity," Tokyo: Science and Technology Agency, 1988.

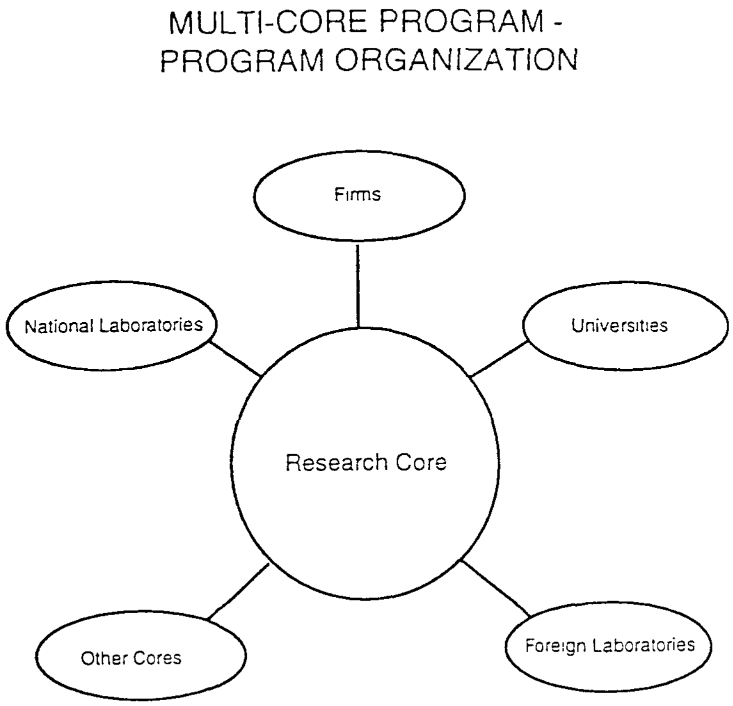
MULTI-CORE PROGRAM -
PROGRAM ORGANIZATION

Figure 24 Schematic of the Organization of the Multi-Core Program

The primary incentives offered by the program are 1) the expertise available at each core and 2) the laboratory facilities for cooperative research. Unlike ISTEC where one of the important initial steps was the development of an expertise in this area among staff dispatched by the member firms, the STA laboratories advertise an expertise that already exists. For firms with a more defined technical interest and with a good match with one of STA's cores, the Multi-Core Project can be a more direct way of filling their needs.

In addition to its expertise, each core advertises its facilities as being available to research cooperators. If the facilities are particularly unique or expensive to acquire, their availability at the core laboratory can provide a major incentive for collaboration. This can be particularly attractive for university professors and small firms. Even if a firm has made the investment in an advanced piece of equipment, it may still want to improve the skills of its staff in analyzing materials such as superconductors. The cores can thus provide a useful training and research resource. In both instances of accessing expertise and accessing facilities, the potential benefit to the participating organization can be more clearly defined than in the case of multilaterally cooperative programs such as ISTEC.

By STA's definition, these themes are divided into three general areas: 1) processing, 2) characterization, and 3) theory and data base. Seven of the centers are categorized as processing, five as characterization, and one as theory. The processing category includes the themes New Superconductors, Component Purification, Thin Film, Single Crystal, Lithography, Basic Conductor, and Space Environment. The characterization category comprises the themes High-Field Properties, Crystal Structures, Chemical Compositions, Radiation Effects, and Physical and Chemical Analysis. Finally, the Theory and Data Base activities each have their own core. Later we will analyze how these core themes, their facilities, and cooperative research activities fit into innovation in this field.

The technical themes for each of these core are summarized in Table 11.

The mention of practical application in the mission statement of the project along with the large number of processing cores and the lack of a category more clearly indicating fundamental materials research has led some observers to the impression that the Japanese are again plotting to capture the benefits of international basic research by targeting processing and applications, neglecting tasks central to the field such as the search for new material compositions. [89] However examination of the content of each of the cores shows this not to be the case. The five centers which fall under the heading "characterization" are each directed toward basic studies of the material and its behavior in altered environments. Analyses of crystal structures and chemical compositions is being pursued through a breadth of tools for basic research such as high resolution electron microscopy, x-ray diffraction, ion-scattering spectroscopy, and muon resonance spectroscopy. Under the heading of Basic Conductor is a core directed toward the "exploration of new superconductors" in which researchers are using both solid state and liquid/gas reactions to synthesize new materials. Dr. Maeda has noted that although his activities are ostensibly directed toward processing techniques, they have also experimented with new material compositions as have many of the other processing cores. His feeling was that the distinction between processing and fundamental studies is not a distinct one at this stage in the development of this material.[90]

### The Incentives

The organization of the SRL and the Multi-Core Program are thus based on general research themes, and have been created with the intention of being operated as common research facilities. However the participants come with a variety of interests which are

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[89] Michael Crow, "Technology development in Japan and the United States: lessons from the high-temperature superconductivity race," Science and Public Policy, Vol. 16, No. 6, December 1989; or B.R. Inman and Daniel F. Burton, "Technology and Competitiveness: The New Policy Frontier," Foreign Affairs, Spring 1990; Japan Technology Evaluation Center, JTEC Panel Report on High Temperature Superconductivity in Japan, Washington: NTIS, November 1989, p. xi.

[90] Interview with Dr. Maeda, National Research Institute for Metals

Table 11 Multi-Core Project Research Themes

| Category | Multi-Core Theme | Host Laboratory |
|---|---|---|
| Theory and Data Base | Theory | NRIM |
| | Data Base | Various |
| Processing | New Superconducting Materials | NIRIM |
| | Material Composition | NRIM |
| | Thin Film | NRIM |
| | Single Crystal | NIRIM |
| | Lithography | RIKEN |
| | Basic Conductor | NRIM |
| | Space | NASDA |
| Characterization | High Field | NRIM |
| | Crystal Structure | NIRIM |
| | Chemical Composition | RIKEN |
| | Radiation | JAERI |
| | Physical and Chemical | MRS |

likely to affect the form of the organization and its ability to achieve communication and cooperation.

In brief, the most significant tension in the organization of the collective activity is the tension between the desire of the firms to appropriate developments and the desire of *the collective to diffuse information.*

ISTEC's and Multi-Core's goals, emphasize the collective advance of the science and technology of superconductivity for the general benefit of science, industry and society. In an ideal sense, then, the activities of the programs are not to appropriate their research results, but to diffuse their developments for the general good. By contrast, the goals of the participants are much more varied, and to the extent that the participants expect to benefit from commercial exploitation, the goals are focussed on appropriation rather than diffusion. Firms can be expected to vie for their best position in the consortia.

Thus, for example, for firms seeking to advance their core markets, the incentive would be to participate in that part of the center which addresses the most relevant technologies or technical barriers. For materials suppliers, we would expect a bias toward fundamental performance improvements through composition or processing. For device manufacturers we would expect an interest in processing related closely to the barriers to the realization of the device. For systems users, integration and prototype testing might be expected to be of primary interest.

For ISTEC, the organizational challenges are more severe as the center is trying to gain cooperation among diverse and sometimes competing interests. The center aims at true cooperation. By contrast, as firms in Multi-Core engage in bilateral agreements with the core of interest, the potential for conflict between the participants or with the collective is much reduced. Unlike the collective arrangement in ISTEC, each firm in Multi-Core arranges a bilateral agreement with the core laboratory and does not rely on the success or even participation of other firms. Although this means that the firms will not have whatever collective learning and brainstorming benefits that might arise in a larger collective facility, there is a greater chance that the advances might be appropriated for some time and that the research will stay closer to the firm's interests. The disincentives associated with undesired leakage of advances made by a firm's researcher, or about the technical interests or level of advancement of the firm, are thus reduced.

For example, since insulation from direct exposure to competitive interests reduces the disincentives to cooperation, we would expect less conflict between resource rich and resource poor firms, or between experienced and inexperienced firms. To the contrary, we would expect to see both groups participating. The participation of larger or experienced firms would confirm that truly state-of-the-art work is underway which is of interest to frontier research teams. The presence of small firms would be expected and would indicate the program's accessibility and would be a sign of the program's contribution to the diffusion of research activity in this area.[91] We would expect firms to be more interested in

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[91] However, as researchers from the various firms are likely to mingle in the same laboratory, it may be true that a successful measure of activity for the collective may reduce the incentive of individual firms to participate. A large number of industrial participants in the program appears to be one of the measures of success for STA, indicating the importance and relevance of the program's research. MOF likes to see a large number of other organizations are participating, sharing the burden of research, with industrial participants being particularly attractive as they indicate commercial relevance in the activity. As the number increases, however, so do the opportunities for contacts with researchers from other laboratories. Even though the bench work may be separate, some transfer of knowledge is likely to occur. To the extent that the work is shared in the open literature and is still viewed a positive sum activity through the sharing of ideas, the benefits will outweigh the penalties and the incentives support participation. This would be expected to be more the case for fundamental research. To the extent that the work has

the cores with expertise that are more relevant to commercial ends than in the basic research core, and we would expect the opposite with university professors.

An analysis of organizational patterns of participation will illustrate differences between a collective system in which participation more directly reflects the primary interests of the firms. Areas in which the interaction between the incentives of the firms and the shape of the collective will be examined include staffing, administration, industrial clustering, and segregation by technical interest.

### Staffing

If each firm is trying to maximize its benefit and minimize its cost, then one would expect some tendency to free ride: to send less qualified researchers. This has been a major problem with consortia formed in both the United States and Europe. For the collective this problem can lead to disaster, for if one firm thinks this way, the other are likely to think this way as well and a downward spiral could result in uniform mediocrity. When organizing the Microelectronics Computer Corporation (MCC), Admiral Bobby Inman insisted on screening all of the researchers nominated by the supporting firms, and initially rejected 95% of the candidates.[92] When organizing the VLSI research laboratory, Sakakibara has noted that the Laboratory Director, Yasuo Tarui, directly selected many of the researchers that participated rather than abide by company nominations.[93] Is there evidence that ISTEC was able to avoid this problem?

In the case of ISTEC, the companies have the right to decide who they want to send. However, Dr. Tanaka noted that this was often done in consultation to try to generally match ISTEC needs. Mr. Ishiguro, head of the Planning Section and dispatched from MITI, more forcefully asserts that he was careful in screening each of the applicants to assure their quality.

What does the evidence show of staff quality? In Japan, the educational system is marked by a rather clear hierarchy of schools. Unlike the United States where there are large clusters of schools considered first-rate, the ranking is more discreet in Japan. Thus at the top of the heap are the national universities led by Tokyo University, Kyoto

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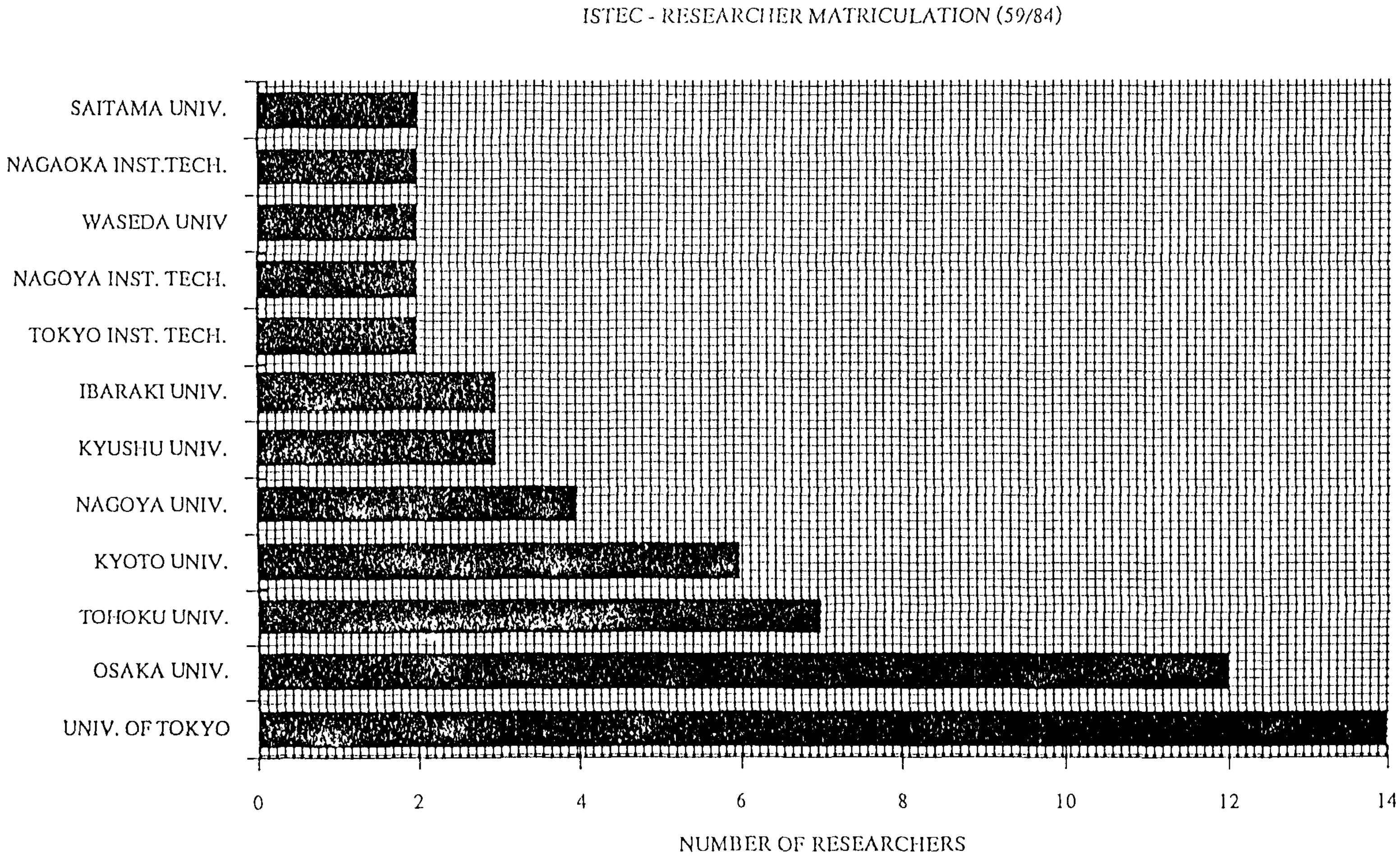
advantages in appropriation, however, the greater number of participants may discourage the more advanced firms from joining. This may be the case in the more applied research activities.

[92] Bobby Inman, "Collaborative Research and Development," Commercializing SDI Technologies, Steward Nozette and Robert Kuhn eds., New York: Praeger, 1987, pp. 63-67.
[93] Kiyonori Sakakibara, op.cit.

Figure 25 Matriculation of ISTEC Researchers



University, Osaka University, and in engineering, Tohoku University. Of similar ranking is one national technical institutes, the Tokyo Institute of Technology, with others being of lower prestige but still considered solid schools, such as the Kanazawa Institute of Technology and the Nagoya Institute of Technology. Close behind are the top private schools, led by Keio and Waseda Universities. Minor representation by graduates of these schools would be an indication of some weakness in staff.

Figure 25 shows the schools whose graduates are most prominently represented within the ISTEC laboratory. The university most prominently represented is the University of Tokyo with 14 graduates. This is closely followed by Osaka University with 12 graduates, and then by Tohoku University, 7 graduates, Kyoto University, 6 graduates, and Nagoya University 4 graduates. Of the 81 researchers in the laboratory, 50, or 60 % are either from top national universities or top private universities, supporting the conclusion that Dr. Tanaka has managed to recruit a research staff of rather high quality. A long-term visiting scientist to the laboratory form the Los Alamos National Laboratory in New Mexico, Jeffery Willis, also made the comment that the staff, overall, was first rate.[94]

How was this accomplished? The reasons distilled from interviews appear several-fold. First there is the attraction and reputation of Prof. Tanaka as the nation's leading research figure in HTS, an unusual blessing for a consortia project. Prof. Tanaka's retirement from the University just as the center was opening was extremely fortuitous. Second, many of the participating firms are considered the "best" firms in the nation and so are able to hire graduates from the best universities. The dispatched researchers are not likely to be among the few such researchers in the firms. Third, there is training function in fundamental research of this exercise. Unlike development or systems oriented projects, a principal gain to the firms will be in the enhanced basic research skills of the researcher, hence reducing the skill of the dispatched researcher directly reduces the return to the company.

Finally, there is the "shame" effect that companies often refer to. If other firms are making a substantive commitment to a collaborative endeavor, the social stigma attached to appearing to be a free rider was often implied as a pressure to maintain some standard.

*Drawbacks*

One of the drawbacks to the reliance on dispatched researchers is that at some point, the companies would like their researchers back. A typical rotation to the

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[94] Interview with Jeffery Willis, July 3, 1991.

Superconductivity Research Laboratory would be between two and three years. After this point the companies tend to feel that their researchers have received adequate training and they would like them to contribute their training to the firm's research. For ISTEC, however, it is at this point that the researchers can begin to make significant individual contributions to the science and, as the pursuit of fundamental science is a long-term process, personnel rotations every two to three years are disruptive. Just as the laboratory fully running and the people trained, the period for rotations will come up, requiring the directors to start all over.

This specter of loss is even more significant when one recalls that SRL was largely staffed over a period of six months. In a short period of time there is potential for major personnel rotation leaving little overlap of the first generation staff with the second.

ISTEC has anticipated this and is working to stagger and delay rotations to the extent possible, but strength in this negotiation will require the backup of MITI.

Long-term continuation requires that the researchers do largely return to their home firms, as defections would make firms increasingly apprehensive about sending good researchers who might move on. This is a strong disincentive faced by firms in the United States. As of the middle of 1991, a few such defections have been reported, with researchers largely returning to the laboratories from which they came.

### Administrative neutrality - Administrative stability

If firms suspect other firms are vying to appropriate or maneuver themselves into a favored position, then the question of who leads becomes a strategic issue. Does it go to the member which is clearly strongest with the assumption that there will be more to contribute from their in-house insights? Does it rotate? Or do they need to recruit externally?

For the ostensible purpose of maintaining neutrality in the management of research in ISTEC, the Division directors were all recruited from neutral organizations. Managers at ISTEC are quick to note that this element of neutrality is consider a key factor for successful operation. The director of Division 1, Naoki Koshizuka, was recruited from MITI's Electrotechnical Laboratory. Hisao Yamauchi, of Division 2, was recruited back from Canada where he was on staff at the University of Windsor. Yuh Shiohara, the head of Division 4, was lured back from this position as an Associate Professor at MIT. Tadataka Morishita, the head of Division 5, came over from the research staff of NHK's Science and Technical Research Laboratory, and Yoshihisa Ishiguro, the head of the

Table 12. Initial Division Directors in ISTEC

| Division | Name | Prior Affiliation |
|---|---|---|
| Division 1 | Naoki Koshizuka | ETL-MITI |
| Division 2 | Hisao Yamauchi | University of Windsor, Canada |
| Division 3 | (Shoji Tanaka) | |
| Division 4 | Yuh Shiohara | M.I.T., U.S.A. |
| Division 5 | Tadataka Morishita | NHK |
| Division 6 | Yoshihisa Ishiguro | MITI |
| Nagoya | Izumi Hirabayashi | Max Plank Research Institute, Germany |

Planning Section and nominal head of Division 6 was dispatched from MITI. Finally, Izumi Hirabayashi, the Director of the Nagoya Division, was recruited while conducting research at the Max Plank Research Institute. These past affiliations are summarized in Table 12. With the exception of the MITI member, the key to the selection of these individuals was their connection to Prof. Tanaka.

As this is largely a fundamental research effort, however, it is not clear how critical are the neutral organization affiliations for efficient direction of the research. More than the fear of biasing the directions of the research, which in any case are set in consultations with other members of the laboratory, there may be concern over the danger of creating interfirm antagonisms should any decisions have to be made. If one member feels disadvantaged as the result of a negotiation, it may work directly against relations with the mediating firm. The reverse consequence would be that to avoid this type of friction, the mediating firm representative will avoid making difficult decisions.

MITI's earlier experience with the VLSI joint research laboratory in the late-1970's highlighted the importance of this mediating function. During the length of this program, one of the principal contributions made by the Managing Director, Masato Nebashi, an *amakudari* bureaucrat from MITI, was to keep relationships lubricated. In an interview with Sakakibara, Nebashi noted that "... All I did for this four years was to drink with them (the researchers) as frequently as I could. I wanted to understand their complaints on those occasions and tried to eliminate problems."[95] By working daily to diffuse tensions,

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[95] Sakakibara, op.cit., p.23.

Nebashi was able to significantly mitigate the high levels of mistrust which existed at the programs outset, enabling the program to function more like a collaborative effort after a couple of years.

Also important in this management arrangement, however, is the desire for continuity. With the staff rotating in and out every two to three years, the Laboratory needed some way to enhance an accumulation of knowledge and to mitigate the negative influences of the turn-over in its staff. For example, although less than six months into actual research, Dr. Yamauchi, noted his concern that just as they will begin to make progress in their search for new materials, the researchers will be called back to their laboratories.[96] Someone has to know what has been done thus far, what approaches have succeeded and failed, and what directions were selected and why. If the Directors are also dispatched from firms, they will also be subject to this personnel rotation, making such continuity difficult. Using lower level research staff as the source of memory may just leave them in constant battle with their Directors. Thus, by recruiting directors as full time staff for longer periods, perhaps the duration of the program, this continuity is placed in the individuals who have the most authority to be able to use the knowledge.

### Industrial Clustering

Whereas the collective would like the participants to pursue research based on the scientific priority of the questions with an eye to the long-term advance of the field, the firms would be expected to be interested in the activities most critical to commercialization, or to shoring up their scientific weaknesses. Thus, for example, electronics firms would be expected to be clustered in Division 5 of SRL, which is thin film research, or the Thin Film or Lithography Cores of the Multi-Core Program. Cable manufacturers would be expected to be more interested in chemical processing of bulk materials and films (Division 4) and high current research (Nagoya Division) of SRL and Multi-Core's Basic Conductor activity. Observers in the Japanese press had predicted that there would be a rush to these processing divisions to the neglect of more theoretical or fundamental research.[97,98]

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[96] "Looking Backward and Looking Forward at SRL," ISTEC Journal, Vol.2, No.4, 1987, p.10.

[97] "Chodendo Kogaku Kenkyujo ni Mekeru Kigyo no Netsui," op. cit., p.13.

[98] Although in general, one would expect to see greater interest in the processing-related sections than in the more fundamental research sections, this might not be true of firms that feel their work is already substantial in superconductivity. In this case, the opportunity for sophisticated theoretical training in the laboratory may prove a more enticing lure. That is, the more well staffed firms might be found in disproportionate number in the fundamental research divisions, Divisions 1 and 2 at SRL and the theory-oriented activities of the Multi-Core Program, reflecting this emphasis on training. Unfortunately the identity of specific firms was withheld so this analysis was not possible.

If, on the other hand, the scientific work was receiving priority, then one might expect to see a division based more on disciplines.

First industrial clustering will be examined.

Figure 26 shows the representation of industrial sectors in each of the ISTEC divisions. The figure reveals that the organization is marked more by industrial dispersion than by thematic clustering. The cable manufacturers, for example are evenly represented in Divisions 1,2,4 and 5. The combination of home electronics firms and telecommunications firms is also rather evenly represented, with a slightly higher weight in thin film research and research of the physics, but with no representation in the high current work. Representatives from the utilities are also distributed through all sections, but again with little interest shown in organics or fundamental materials.

Somewhat more predictable are the interest of the chemical firms in property research and processing, the presence of only one firm in Division 4 which is chartered with the organic materials work, and a weaker overall interest in the basic physics.

The less predictable clustering occurred in the concentration of ceramics firms in the Nagoya division and the proportionately large number of iron and steel representatives in the fundamental physics section. In both cases the phenomena seems to be the result of giving weight to the individual choices of the researchers. In the latter, the researchers dispatched designated theory as their area of interest, and in the former, the participating researchers who have expressed a geographical preference to be in Nagoya. Six of the nine organizations that dispatched researchers to the Nagoya are from the Kinki (Nagoya) region. These include individuals from NGK Spark Plug, NGK Insulators, Toyota, and Chubu Electric. Further, an independent researcher recruited from the University of Tokyo, Dr. Setsuko Tajima, who is formally in Division 3, has selected the Nagoya lab as her husband is at the nearby Okazaki Research Laboratory, directing the high temperature superconductivity research underway there.

In the Multi-Core Program, by contrast, firms are free to select the core in which they are most interested, and as a consequence the preference for commercial relevance is more clearly seen.

Unlike MITI's ISTEC project, it was not necessary to have a critical mass of firms to enable the venture, the core laboratories can fully operate as independent research entities

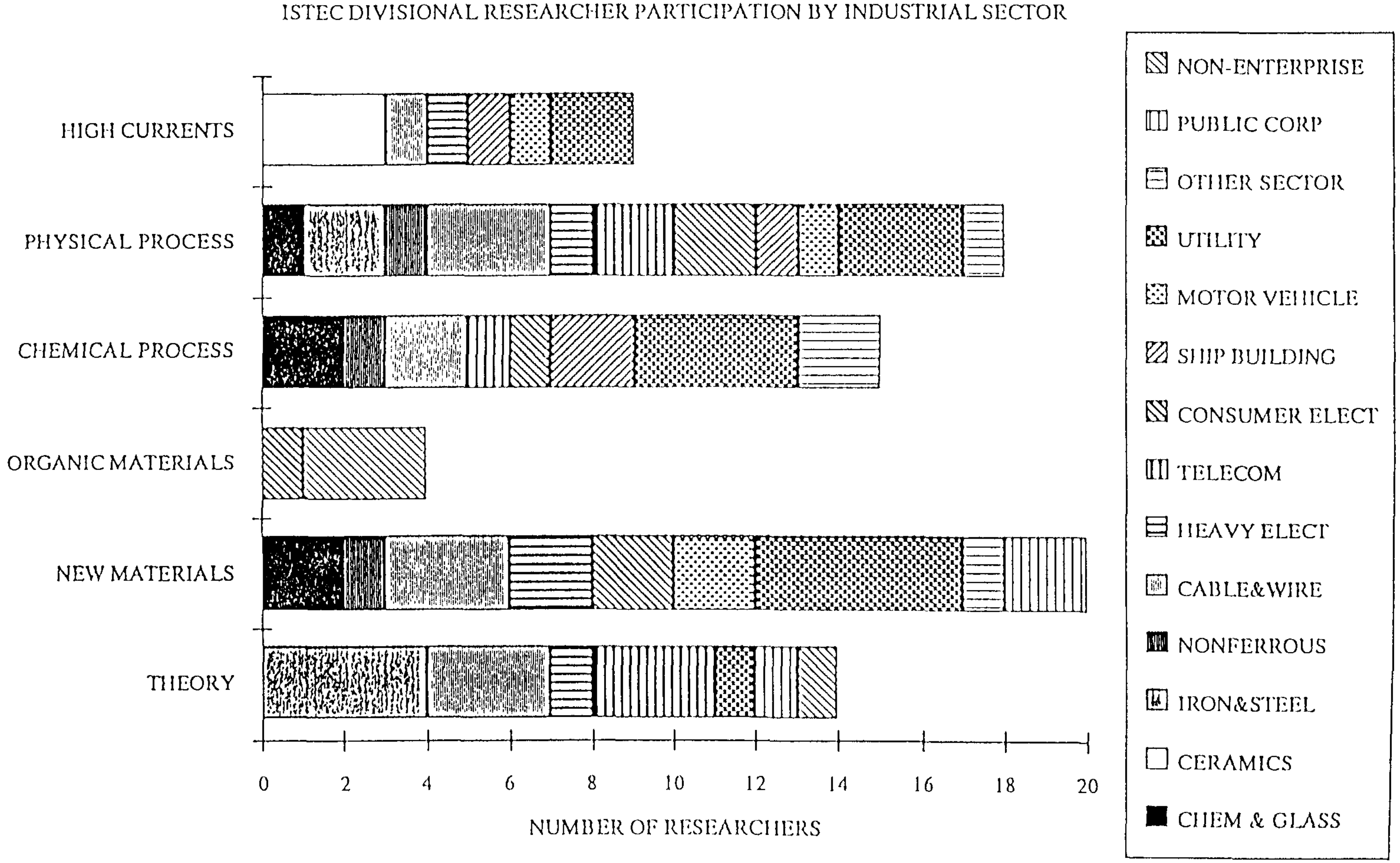


Figure 26 Industrial Sector Distribution in ISTEC Divisions

Figure 27 Industrial Sector Distribution in Multi-Core Program Cores

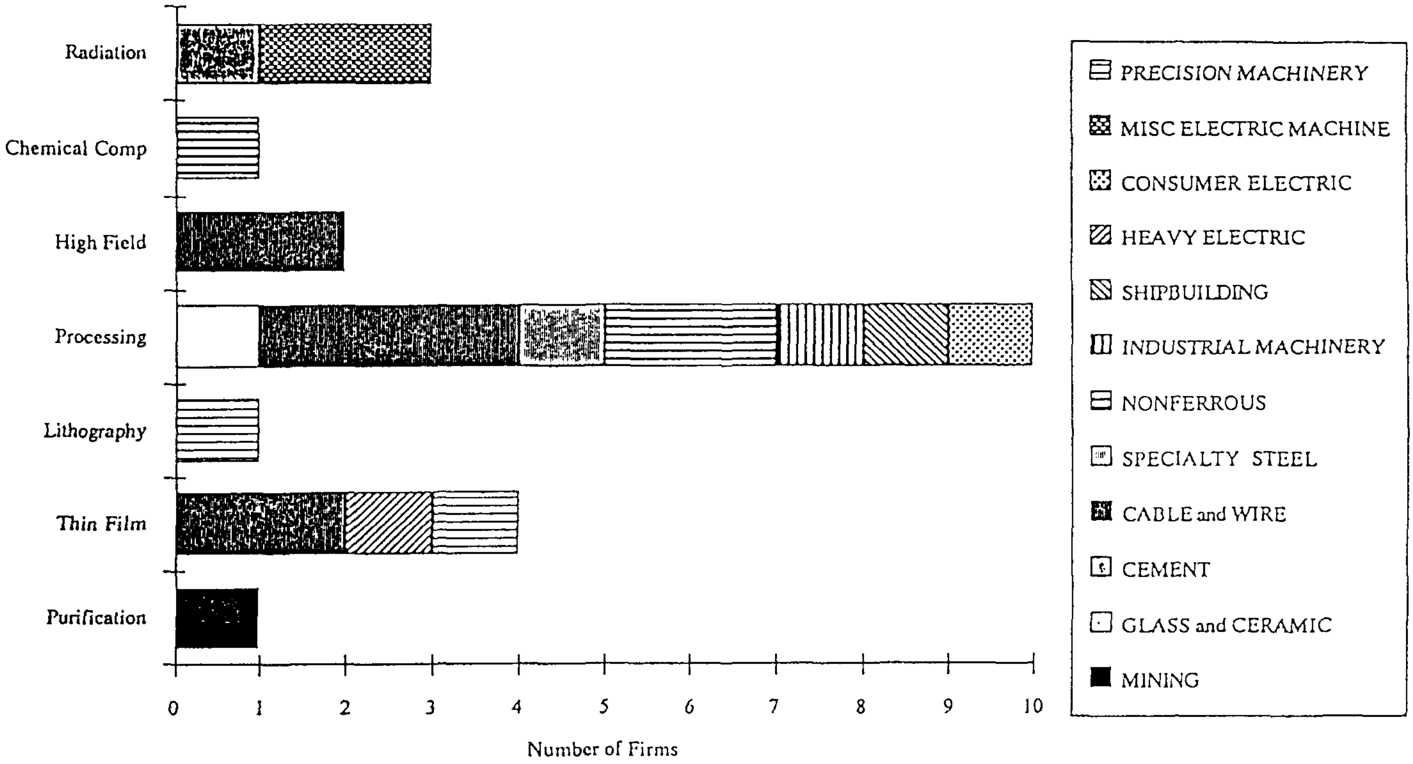
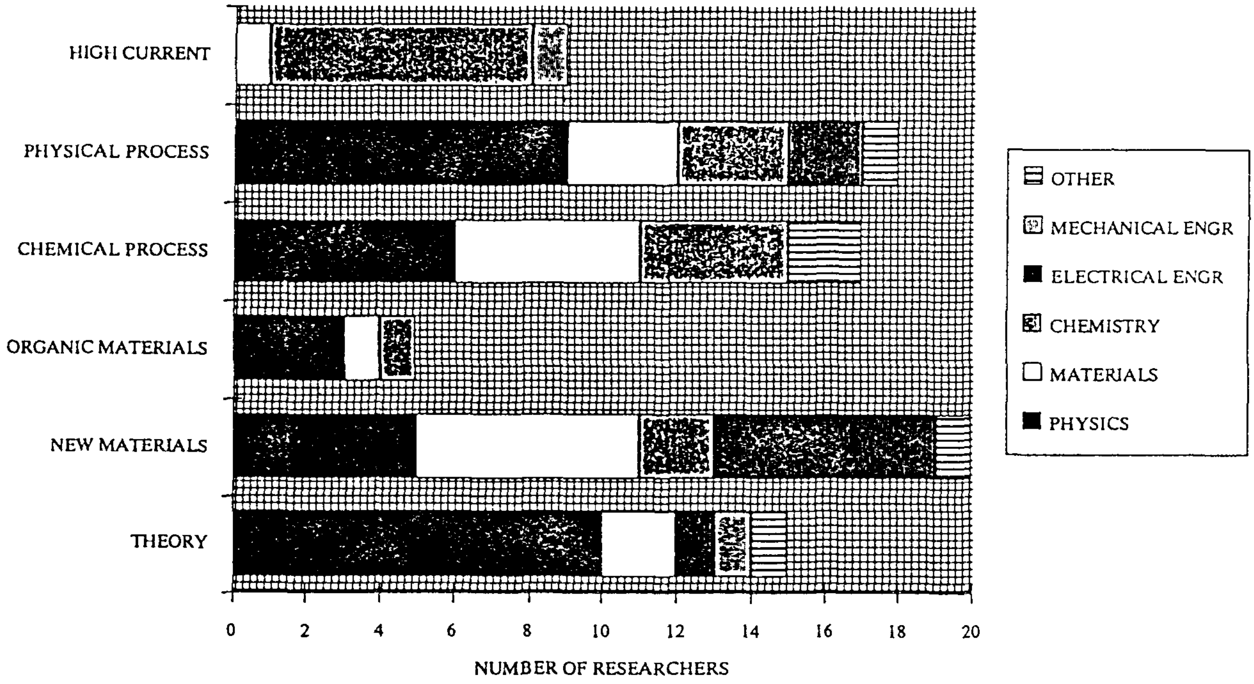


Figure 28 Research Speciality by ISTEC Division



without any participation by industry. Firms, as stressed by an STA official, will participate because of the attractiveness of the science being promoted.

Figure 27 shows participation in each of the cores divided by industrial sector. Twelve different sectors are represented in the various cores of the program. The largest number of the firms, however, are from the Cable and Wire sector, the sector that has been traditionally most active in superconductivity. All of the major cable and wire manufacturers that have been involved in the superconducting industry are participating in this program and are found in one of three of the program cores: Basic Conductor, Thin Film, and High Field. The selection of these cores indicates that these firms are most interested in research that is generally the closest linked to commercialization.

### Distribution by academic speciality

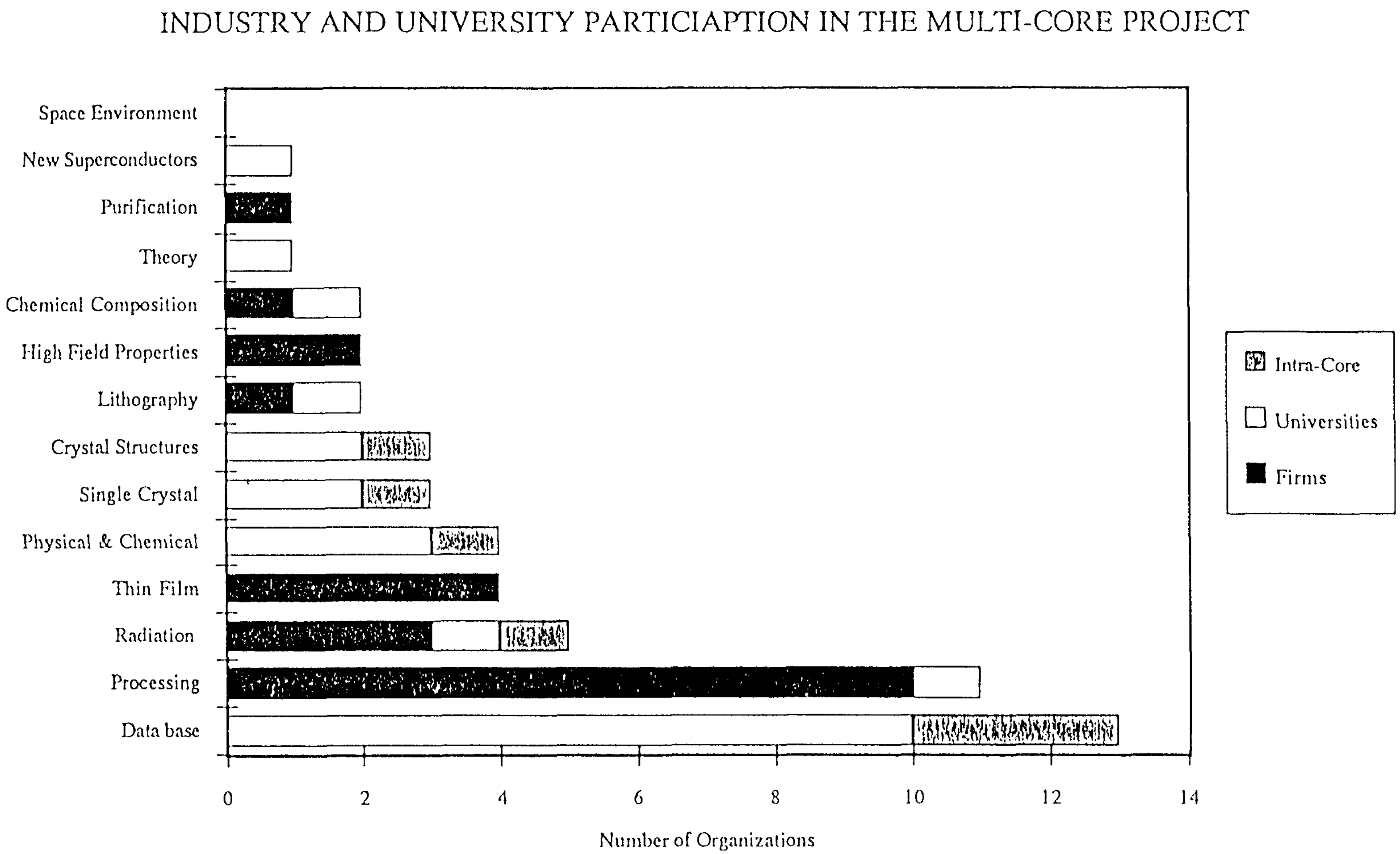
In contrast to the lack of clear patterns in firm participation by divisions in ISTEC, a more distinct separation by specialities occurs when one examines the academic backgrounds of the researchers. This is shown in Figure 28. The clearest concentrations in speciality occur in the theory oriented division, Division 1, and the Nagoya Division. In Division 1, 10 of the 15 researchers come from a physics background and another 2 from materials science. In the Nagoya Division, 7 of the 9 researchers come from a chemistry background and another from materials science. ISTEC representatives interviewed indicated that there was a general desire by dispatching firms in the Nagoya area to emphasize materials and ceramics skills as that is considered one of their unique characteristics.

The one surprise might be the large presence of electrical engineers in the basic materials group, Division 2. This appears to reflect the importance of advance instrumentation in conducting the materials analyses desired, and the fusion of skills necessary to continue promotion basic research in this field.

In the Multi-Core Program, differences appear between the interests of industrial and university participants. It is frequently argued that companies will be much more interested in skills or capabilities that can be used to bring products to market sooner rather than later. Whereas university researchers are often assumed to be interested in more basic questions of the structure and behavior of materials. The data confirms that this is how participation is divided.

Figure 29 shows participation in the various cores by university and industrial organization and shows that there is indeed some segregation of interests between industrial

Figure 29 University and Industrial Participation in Multi-Core Program Cores



and university participants. Again, the heaviest industrial participation is in Dr. Maeda's Basic Conductor core, which is perhaps the most clearly directed toward generically applicable processing issues. Here the industrial cooperators are pursuing techniques such as CVD, sputtering, laser melting, silver sheathing, sol gel, and multifiliment construction. CVD and sputtering projects are being pursued by several participants, which may be a reflection of the general notion in Japan that these two techniques are the most suited for scale-up and manufacturing.[99]

Dr. Maeda's core is followed in popularity by Dr. Ogawa's Thin Film Core which is also directed toward process focussed research. Research addressed includes film layering techniques for bismuth compounds, bismuth film processing in a lead vapor environment, and film growth techniques.

In both the Basic Conductor and Thin Film cores, the industrial presence noticeably outweighs the university presence.

The more popular cores among university professors are the physical and chemical, single crystal, crystal structure, and data base cores. Research in the first three of these cores is directed toward more basic studies of material structure and behavior. In the physical and chemical analysis core, subthemes include surface, microarea and trace analysis of the materials, with the research being conducted using a range of materials analysis tools including XPS/ESCA, XRD, SIMS/IMA, Auger spectroscopy, SEM and EDX. The single crystal core addresses themes such as flux formation and pinning, grain boundary formation, and crystal growth analysis, all areas which are also important for developing and confirming theories of material behavior. Finally, the crystal structure core aims at the analysis of the atomic and electronic structure of HTS materials through X-ray and neutron scattering, ESCA, high precision electron spectroscopy, and by 1991, through an electron microscope that will have a resolution on the order of 1 angstrom, the most precise in the world.

The knowledge gained is, however, more removed from application than the research targeted toward processing questions, and the information is more difficult to appropriate. This type of research is also commonly shared in the scientific literature, which further complicates appropriation. In each of these three core areas, there is no private sector participation.

Although not research, the data base activities of Multi-Core are by far the most highly subscribed by university participants. As such a data base would serve as a

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[99] Japan Technology Evaluation Center, JTEC Panel Report on High Temperature Superconductivity in Japan, Washington: NTIS, November 1989, p. 121.

common resource for the research community for tracking the progress being made by a very large member of institutions within Japan and abroad, an activity very consistent with the traditional role of universities in Japan, and as professors actively compete in this publication arena, participation is high. Participation for the professors thus fulfills a role that they are familiar and comfortable with, and provides them with a means of keeping their own research at the frontier of the field. In this case, however, the success of the activity is not at all appropriable and we see that there are no industrial participants.

In execution, then, there are noticeable differences in participation between the more fundamental research cores and those that are process-oriented. This shows that if interested organizations are free to be technically segregated, such segregation will occur: a confirmation of the rational actor assumption.

### Modes of Operation

The differing incentives to participate also affects the participation options offered by both ISTEC and the Multi-Core Program. As mentioned earlier, in ISTEC, the program offers "Regular" memberships in addition to the "Full" memberships. The Regular Membership allows those with an interest in closely monitoring developments in the field to do so with little financial commitment. A level more elaborate is the system offered by the Multi-Core Program in which the program tries to meet a variety of levels of research commitments.

Outside organizations come with a range of capabilities and levels of commitment to HTS which to some extent must be accommodated in the core. University professors are limited in time and money but can bring a good deal of expertise to the project. Firms with the ability to dispatch a research to become expert in the area of research targeted by a core may find full immersion in the research environment of the core most attractive, whereas firms that are just exploring the possibility of entering the field and firms with discreet experimental needs may be more interested in using the core facilities for testing than for training, seeking to avoid the cost of committing a researcher.

In operation, there are three principal modes of cooperation for the core: user facilities, common research and training facility, and parallel task facility. In all cases, the user or cooperating organizations are responsible for bearing their own expense of participation.

For the university professors that participate, the core have tended to serve as user facilities. The research equipment in most universities in Japan is often inadequate to allow the researchers to conduct frontier research. The accessibility of facilities at the government laboratories can therefore be very attractive. In addition, professors do not have the flexibility of time to commit themselves full time to the research, as would be required for example at ISTEC, but they can use the facilities efficiently through a more part-time, as-needed schedule.

A second mode is as a common research facility. Formally, each of the cooperating organizations enters into a bilateral contract with the core laboratory, defining the scope of the research as well as guidelines for the division of intellectual property rights. Thus in form, the tasks of the cooperating entities are insulated from each other.

However, interviews with researchers have indicated that the separation is much more one of form than of substance. At the National Research Institute for Metals, for example, the five researchers currently on assignment from companies are treated largely the same as the other research staff and mingle just as the normal staff does. Dr. Maeda, head of this activity, noted that the research is still so far from application that commercial concerns are low. Since they aren't really sure about what they should be hiding, in practice they have accepted the more positive strategy of progressing through mutual learning and the exchange of ideas. Unless developments are unambiguously traced to the sole work of a dispatched researcher, the patents will likely be given to the national laboratory.

Thirdly, in some cases, the research at the laboratory is coordinated with research at a cooperating organization without the transfer of personnel: the research task is partitioned. A task, for example, is proposed in which companies share materials and data with the core lab. The researchers at the core laboratory work on the definition of the research with the cooperating researchers, but the work is conducted in the separate laboratories. In this way skills and data were made available without the need to move personnel.

Because of the various modes of collaboration with each of the "cores," guidelines on intellectual property assignments have been left flexible, as mentioned earlier. As a general principal, when a dispatched researcher makes a discovery while working at one of the centers, the property rights are nominally to be divided evenly between the dispatching organization and the STA. However, in many cases, STA officials stressed, national laboratory personnel will be leading the research or will conduct the bulk of the research, in which case most or all of the ownership right will be vested in the government.

## The Impact on Innovation

Research into materials that show superconductivity at higher temperatures is still in a nascent phase. There is no certainty about what other materials will superconduct, what brings about the superconductivity, what temperatures or current limits can be achieved, or what processing limitations will prove unmanageable. New HTS materials continue to appear, such as the Carbon-60 compounds which were shown in early 1991 to superconduct, and processing improvements such as Sumitomo Electric's announcement of a 1 telsa high field bismuth oxide magnet in March of 1991 or their announcement of a bismuth magnet that could generate a 2250 gauss field in a 23 telsa environment in May of 1991,[100] continue to challenge doubters of the material's practicality. As both ISTEC and Multi-Core have only recently begun their research, attempts to measure their scientific productivity and impact are certainly premature. However, one can look at structural features of the programs and examine questions such as whether the programs are comprehensive and complementary in their coverage, how they attempt to advance the core science, and how the participation patterns reflect contributions to diversification, diffusion, developing complementary assets, and training.

### Comprehensiveness of Technical Coverage

Given that both ISTEC and the Multi-Core Project nominally address the same concern, the fundamental advance of oxide superconductors, the question arises about the extent to which the programs complement each other. Do the organizations appear to be more or less comprehensive in its technical coverage? Is their work complementary or redundant? Are there noticeable differences in participation or participation patterns?

In Table 13 I have attempted to summarize areas of similarity and difference in technical activity between ISTEC and STA. Both are active in their pursuit of insights about the basic properties of the materials, exploration of chemical processing techniques, thin film processing, and the search of new materials. However for the later two, the level of activity at ISTEC is notably higher than in the core programs.

The reverse is true of the data base activities which both organizations are undertaking. As more purely a common good rather than an appropriable advantage,

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[100] "Kyo Jiba Hassei ni Seiko, Bisumasukei Chodendozai," Asahi Shimbun, March 6, 1991; and "Bisumasukei Chodendo wo Yoite 23 tesura shita de 2250 Gausu Hassei," News Release, Sumitomo Electric, May 13, 1991.

Table 13 Areas of Similarity and Difference in the ISTEC and Multi-Core Programs

| | ISTEC | MULTI-CORE |
|---|---|---|
| Areas of Similarity | | |
| | Theory | Theory |
| | Evaluation of Properties | Physical and Chemical Properties<br>Analysis of Crystal Structures<br>Chemical Compositions<br>- Physical Analysis |
| | New Materials | New Superconductors<br>Purification of Components |
| | Chemical Processing | Single Crystal Analyses<br>Chemical Processing |
| | Thin Film | Thin Film<br>Lithography |
| Areas of Difference | | |
| | Organic Materials | Space |
| | | High Field Research |
| | High-Current Materials | Radiation |

industrial participants seem minimally interested in committing staff to this activity. However the professors in the Multi-Core Project have gathered in this core to a far greater degree than any of the other cores. In ISTEC, by contrast, there were still no staff members assigned to this division, other than the head, by early 1990.

The table also points to areas which the programs are pursuing separately. Two ISTEC divisions that have received little attention in STA address high current materials and organic materials. Because of the relevance for electricity transmission, and the conspicuous presence of Japan's electric utilities in ISTEC, the center has a division looking into processing techniques to develop materials capable of carrying high currents for power applications. STA is absent such a core as the primary constituency for such an application does not come under the administrative eye of STA and is absent from the program. At the other end of the applied-basic spectrum, ISTEC is exploring the possibilities of an even more exotic and poorly understood superconducting material - organic superconductors. This is a field that particularly intrigues Dr. Tanaka as the molecular structure of the materials are far more complex than oxides and metallics, and as the possibilities may be without limit. The STA program is absent of an organic material activity as there was not a similar influential voice in the Multi-Core project pressing for this research theme.

In the STA program, the unique core appear closely related to unique functions of the agency as well as unique capabilities that the laboratories are trying to develop. As described in an earlier section, one near-term possibility for the use of HTS is its application in space. Since space temperatures are on the order of 30 - 40 K, many of the current HTS materials become candidates. NASDA, the National Aeronautic and Space Development Agency, a quasi-governmental organization supervised by the STA, is charged with Japan's development of space activities, a function which does not belong to MITI. STA can thus exercise its jurisdictional authority over this area of development and claim it as more naturally belonging to their programs.

Similarly, JAERI, the Japan Atomic Energy Research Institute, a quasi-governmental organization supervised by the STA, is also charged with functions unique from MITI that assist in carving a research niche. JAERI is responsible for the research and development of nuclear fission and fusion technologies and experimentation with radioactive materials. Although MITI is actively involved with the commercialization of fission, it does not play a significant role in R&D. Furthermore, STA has principal authority in fusion and, as described earlier, fusion experiments require extremely high magnetic fields which require superconducting magnets. As a result, STA's research examining the effect of radioactive materials on SC performance is also unique from the work in ISTEC.

Finally there is the High Magnetic Field core which is primarily a facilities development project to give STA the most powerful laboratory magnet in the world when it is completed in 1992. Here, unlike MITI which is charged with supporting the activities of the industry, STA can leverage its mission of supporting advanced science to justify the investment into a very large research facility. Unlike MITI, STA has much more of a legitimate charge to support big science projects.

So how does participation compare between the areas of program overlap and the areas of unique activity? The greatest participation in both programs are in the areas in which their technical themes of the two programs overlap.

The ISTEC efforts in theory, chemical processing and thin film processing are rather evenly and well staffed, but the activity in high current materials at the Nagoya branch has roughly half this staff level and the organic materials project has less than a quarter. In the Multi-Core program, the space activity has yet to attract a cooperating organization. The High Field core has two industrial participants, but these firms are involved in the design and construction of the magnet rather than in experimentation. Of Multi-Core's activities that are unique from ISTEC, only the Radiation core has attracted actual research cooperators. However, even in this case, cooperation is again with organizations that have already been dealing the institute for its fission and fusion activities.

Why the low participation?

Space is a possible near-term application but the market is limited. High current applications would offer a large market, but commercialization is generally considered more distant than thin film and magnet applications. Application of organic materials is even further away. High field experiments may become popular when the facilities are available, but for most of the duration of the project, this is a construction activity. The technical breadth provided through the unique aspects both the Multi-Core and ISTEC projects is thus much less central to the technical interests of the cooperators than the areas that they are supporting in common: processing and characterization. Comprehensiveness is not as important for cooperation as targeting core issues.

Thus where the programs might be said to be addressing gaps outside of the core interests of the field, we see much less interest in cooperation. This is a relevant warning for others who design cooperative programs to advance a field of science. Cooperators will be much more interested in core capabilities than peripheral gaps, so if gap-filling or a comprehensive program is desired, direct contract research will be more effective. Cooperators aim toward their technical interests, and those interests are seen to be in the core issues of the field.

### Advancing the Core Science - Cooperation as a Political Strategy

Although these programs are designed to leverage cooperation for the promotion of this field, I would argue that one of the most important benefits are the science is separate from the levels of cooperation. For both the ISTEC and Multi-Core Programs a valuable benefit of the cooperative scheme is the political leverage it provides in trying to get a new program funded. For MITI, the cooperative scheme with broad industrial commitment shows the Ministry of Finance and members of the Diet that this activity has significant industrial interest, but which, because of its long-term, uncertain nature warrants government support. Industrial cooperation legitimizes MITI's entry into this field of rather basic research.

For the Multi-Core Program, cooperation similar political benefits which lead to even greater returns to the program. As with government laboratories in the United States, there is an increasing desire among policymakers in Japan as well to see the efficient transfer of the research generated by public bodies to the industry and universities. It is both politically popular and necessary to show how the government's investment in research will make its way into the economy. The cooperative system provides this rationale. Without private sector participation, the chances of getting the program funded would have been much less certain.

Leveraging the symbol of cooperation, both programs were established. But the main contribution to the science was not in cooperation. For both programs it is in the equipment investment that has been enabled and the ability to commit personnel to this task over a long-term.

If enhancing collective research or industrial participation was the goal in Multi-Core, then one might conclude that the goal was only being achieved at a significant cost. If the cost of each core is divided by the number of cooperating organizations, it is clear that achieving cooperation is expensive. In 1989, for example, seven of the core have an average cost per cooperator of between 10 -100 million yen, with two others well above 100 million yen per cooperator. Thus, if the government investment in Multi-Core is judged as the cost of enticing participation, then it might seem like a bad deal. However if it is judged as an investment in new research facilities to address an exciting new field at a time of very tight budgets, and an opportunity to concentrate in-house laboratory personnel, it might be judged a cleverly executed play.

Recall that staffing for the national laboratories is paid for out of the general laboratory personnel budget. Thus when funds are received for big projects such as Multi-Core, almost all of the funds can go to equipment and materials.

The three largest investments that will be made by the project are the development of a 40 T hybrid superconducting magnet and a 20 T large-aperture superconducting magnet at the National Research Institute for Metals, and and an ultra-high precision electron microscope at the National Research Institute for Inorganic Metals.

The largest magnet in the world that is currently available for materials research purposes is a 30 T magnet at MIT, with the university currently building a 35 T system which is scheduled to be completed this year, 1990. Thus, the planned 40 T magnet at NRIM, when completed in 1992, will take its place as the largest in the world. With the 40 T magnet researchers hope to make more precise measurements of critical current densities in superconducting materials, to explore the basic phenomena that would provide for a higher critical current density, and to investigate methods of fabricating wires from new superconducting materials.

Table 14. Magnets to be Housed in the High Field Magnet Center[101]

| Magnet | Cost (Million yen) |
|---|---|
| 80 T long-pulse magnet | 420 |
| 40 T hybrid magnet | 3,200 |
| 20 T large-aperture SC magnet | 770 |
| Super-minute magnetic field measuring system | 450 |
| Center building | 4,800 |

The 20 T magnet is being designed with a relatively large 150 mm diameter testing space which can be used for larger bulk materials specimens. Tests would include high pressure stress tests and electromagnetic stability tests under alternating currents. These two magnets will be housed in the same facility, the High Field Magnet Center, as will a recently constructed 80 T long-pulse magnet and a 16 T system designed for high accuracy and high stability to conduct super-minute field measurements. These magnets and their costs are summarized on Table 14.

The other large piece of experimental equipment to be developed for research in the program is a very high resolution electron microscope which is to be used for the analysis of the electronic and atomic structures of crystals. At an estimated cost of 900 million yen, the device is designed to provide for resolution down to 1 Angstrom, the highest resolution available in the world.

There are, in addition, an array of experimental devices being bought or upgraded through this program. Appendix B lists summarizes the more significant pieces of equipment advertised by each of the cores. Collected in the Cores is an impressive array of advance devices for probing and poking at the new materials. Some of the devices are discreet, as in the Lithography core, some tailored to specific ends, such as at the Radiation Effects core, and some core have a collection of broadly applicable equipment as seen in the Physical and Chemical core.[102]

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[101] NSF Report Memorandum #162, "STA to Build a High Field Magnet Center for the 'Multicore Project,'" August 10, 1988.

[102] However, even though much of the budget for the Multi-Core Project is for equipment investment, it is also true that the major pieces of equipment, which even the largest companies do not possess, will not be available until 1991 or 1992.

The other benefit to the science is the ability to concentrate personnel. Although there are only one or two industrial cooperators in many of the cores, the average number of researchers assigned by the hosting laboratory to a core activity is 10 to 15. The principal beneficiaries of the Multi-Core scheme are therefore the core laboratories, and possibly the science, as it provides for advanced research with state-of-the-art and internationally leading equipment by providing the political key for purchasing advanced facilities for the laboratories.

### Core Enhancement vs. Diversification

Because of the variety of specialities and resources offered through the core laboratories of these two programs, one might guess that the program would have an industrial impact by enhancing the skills of the core industries; or that the program will add to the skills of firms new to superconductivity and encourage diversification. Is there evidence of either core enhancement or diversification? In the discussion below I will examine the extent and depth of diversification by looking at indicators that include the industrial sectors participating, the length of experience of participating firms in superconductivity research, and the size of the in house research staff investigating superconductivity.

First we can look at the relative innovative activity of the firms participating in ISTEC. By comparing these firms with the larger set of firms generally active in HTS, we can see that participants account for a significant fraction of overall activity. Figure 29 shows the number of patent applications in superconductivity offered by full-support members compared with industry totals for all firms submitting two or more applications between early-1987 and mid-1988.

The firms that have the longest history of involvement in superconductivity research are represented in the cable and wire, and the electric machinery sectors. All of the major cable and wire firms except for Showa Denko are participating as full members, and all of the electric machinery manufacturers that have substantial histories in superconductivity R&D are also present with the exception of Fuji Electric.

Figure 30 also shows some effect of industrial diversification, as firms which had not conducted superconductivity research prior to HTS have used ISTEC as a vehicle to get started. These include firms that are largely either potential materials suppliers or likely materials users such as those in the ceramics, iron and steel, mining, shipbuilding, electrical machinery, electronics, and communications industries. Most of the patent

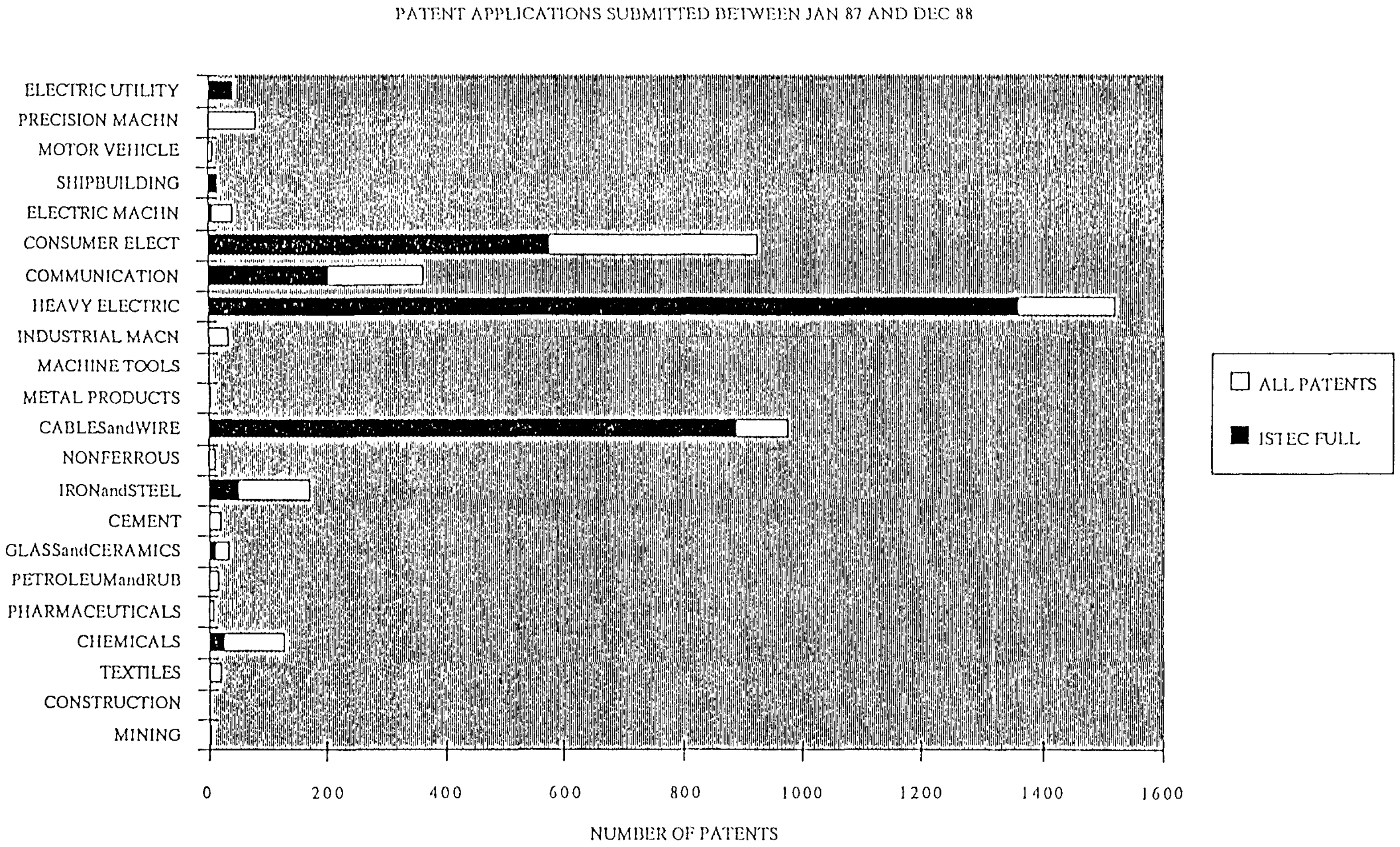

Figure 30 Patent Applications by ISTEC Full-Support Members Compared with Industry Totals

applications by firms in the key materials supply and systems development industries are seen to be from members of ISTEC. The exception is the chemical industry, in which only a small percentage is represented in the center.

In the Multi-Core Program, there are also a broad range of sectors represented by the participating firms. However, in this program conclusions about the influence on industrial diversity must be somewhat guarded as each industry is typically represented by only one firm. Although half of the firms do appear to be diversifying, the collective scale is rather small. Thus in the Multi-Core case, it is more appropriate to say that firms from a variety of industrial sectors show interest in diversification, but that the general effect on industrial-level diversification is limited.

Another indicator of a firm's attempt to diversify is at the newness of the firm's to this field. For those firms with long, established superconductivity programs, participation might be considered more of an extension of its existing capabilities. For firms which have only entered since the discovery of HTS, on the other hand the program is a clearer aid for diversification.

The average number of years in superconductivity among firms in different sectors was shown earlier in Figure 3.14, also confirming the recent migration into the field after HTS. The figure shows that only firms in the Cable and Wire and Heavy Electric Industries have significant experience. In the Multi-Core Program, the cooperating firms are divided between those that have a long history in this field, greater than 10 years, those with a moderate history, between 3 - 10 years, and those that have only entered the field since the discovery of HTS. Figure 31 shows that about one half of the firms are well seasoned, with a long investment in this field, and about one half have only started since the high temperature discoveries. Figure 32 shows that the distribution of these firms is also rather even across the various cores, further supporting the view that both firms seeking diversification and those seeking to enhance their presence in superconductivity are evenly represented in the project.

Thirdly, one can also ask how important participation in each of these programs is to each of these firms. Although the number of researchers per firms may be low, it is the relative impact for the firm that is important. To gauge the relative true impact of participation, it is useful to examine the size of the in house staff working on superconductivity R&D as the project's influence may be more significant for firms that have a small effort.

Figure 31 Length of Experience in Superconductivity, Mutli-Core Program

Mcore.FirmHistory.pie

FIRM HISTORY IN SUPERCONDUCTIVITY R&D AMONG MULTI-CORE PARTICIPANTS

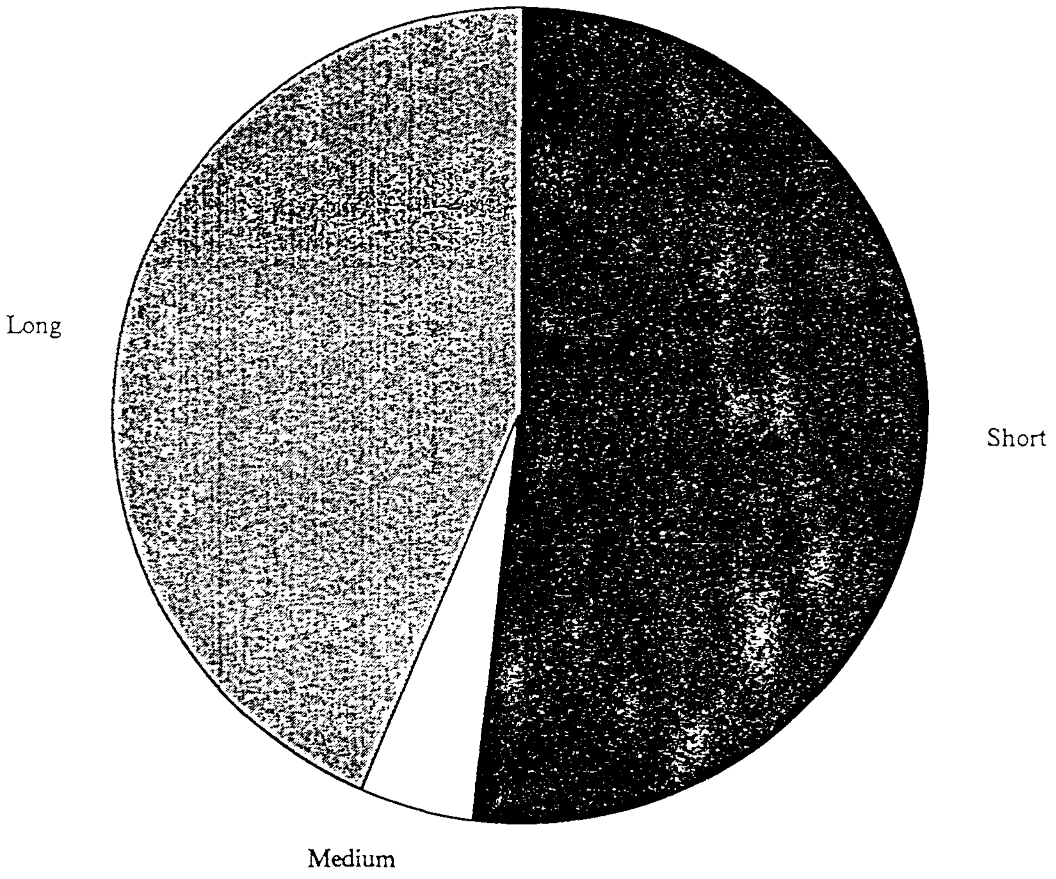

Figure 32 Distribution of Firms in Multi-Core Program

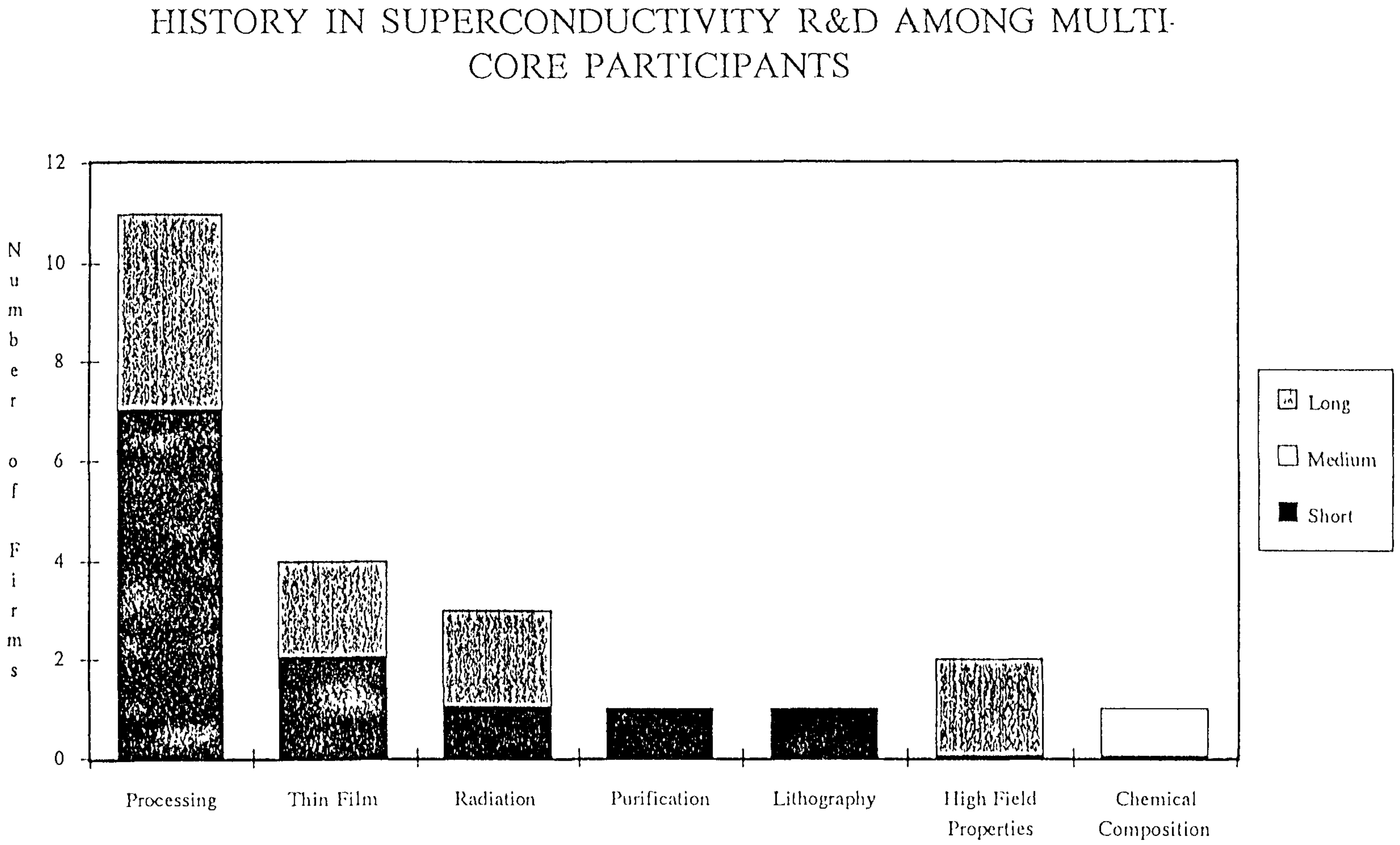

Figure 33 shows an approximation of the number of total researchers working on superconductivity in each of the full support member firms and their ratio with the number of researchers dispatched to ISTEC at any one time: this is fixed at a maximum of 2 researchers.[103] The figure shows that ISTEC's presence is much more significant for firms which are attempting to enter the field. In the chemicals, glass and ceramics, and automotive sectors, the ISTEC researchers represent 40% or more of the total firm effort in HTS. For the sectors most traditionally active in SC, heavy electric and cable and wire, the figure is around 5%. ISTEC participation also occupies a large percentage of the utility research in this area, but recall that the utilities are really acting more like a bank than a technical contributor.

Figure 34 summarizes the level of in house activity of firms participating in the Multi-Core Program. Firms are divided between those that have fewer than 5 in house researchers working in superconductivity, those with between 5 and 20, and those with greater than 20. The figure shows that slightly more than half of the firms have only a small in house staff, with these same firms generally having entered superconductivity since the high temperature discovery. Only one of the participating firms, a major consumer electronics manufacturer, has a short history yet a relatively high level of in house activity. Thus for the participating firms that are new to this field, Multi-Core is a significant element of their investment in this activity. In addition, about half of these new firms are <u>not</u> participants in the ISTEC program, reflecting the lower costs and more flexible terms of participation in research in Multi-Core.

Figure 35 provides evidence that experienced and highly active firms will participate in the same core as inexperienced firms with small staffs working on superconductivity. Since the agreements between the firms and the core laboratories are bilaterally cooperative, not multilaterally so, interfirm dependencies are not significant. Here, common participation is not a significant barrier to entry or to firm level diversification.

Thus with regard to firm level diversification, we can conclude that both ISTEC and the Multi-Core project contribute to both the enhancement of veteran firms in the industry and to other firms trying to diversify. Both large, well established actors and small, new players have found participation to be in their interests, and both participate.

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[103] One can claim that ISTEC will actually train up to 10 researchers as many researchers will be rotated out by their companies after 2 or 3 years, but I'll use a point in time argument (some researchers in the main laboratory will, after all, also be rotated in and out of superconductivity, so this number is not fixed either.)

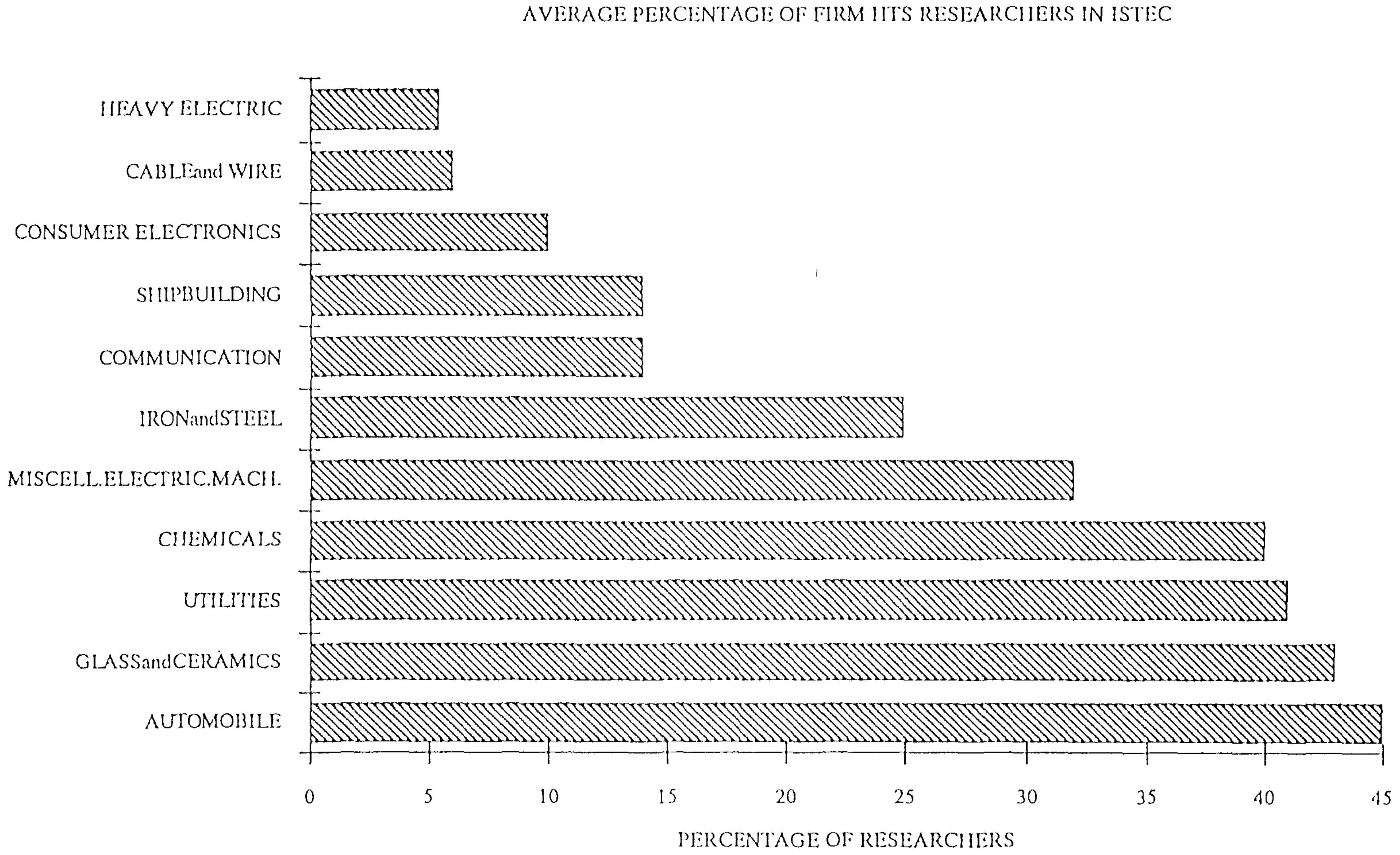


Figure 33. Ratio of ISTEC Researchers to In-House Researchers for Participating Firms

Figure 34. Level of In-House Activity in HTS of Firms Participating in the Multi-Core Program

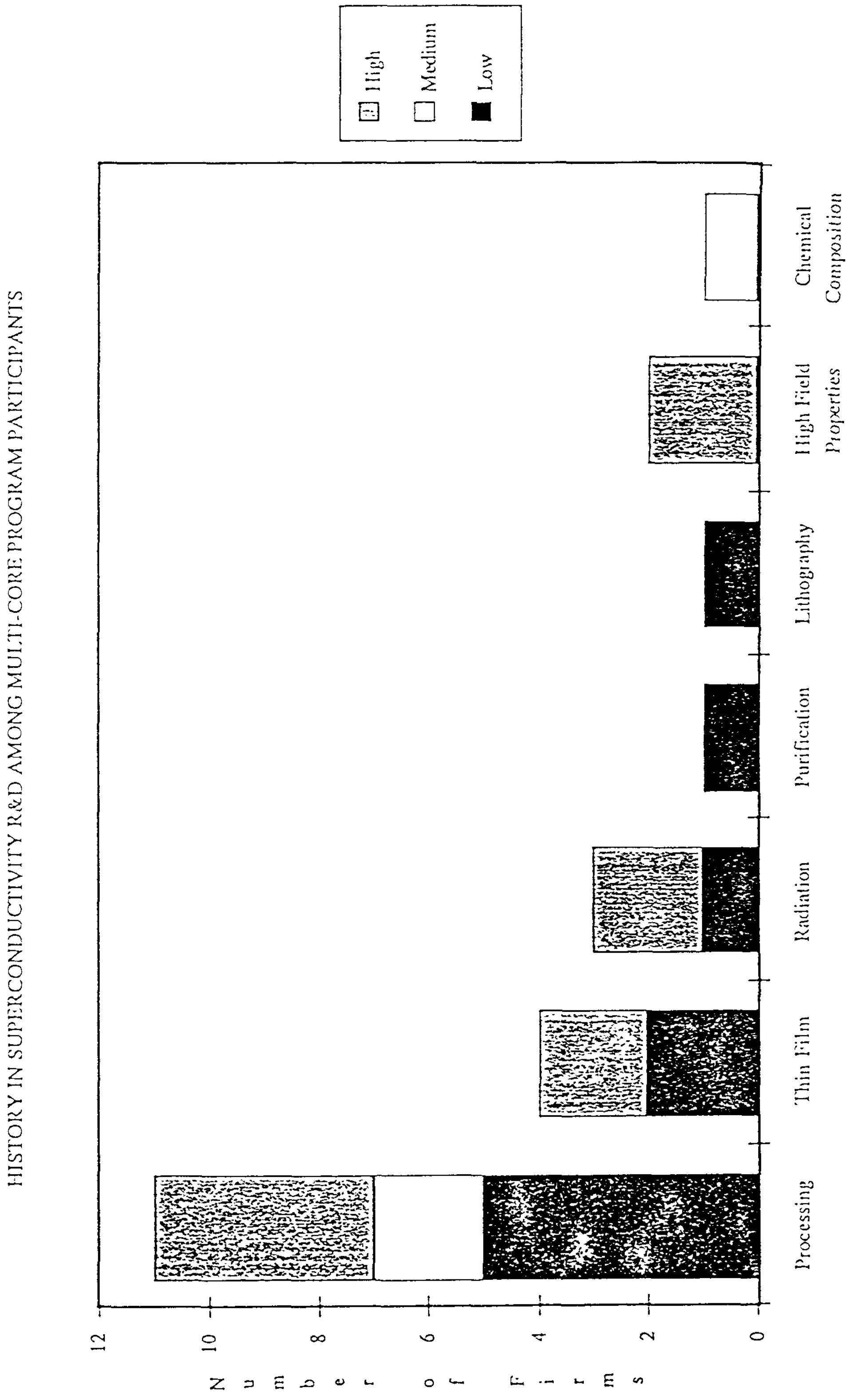
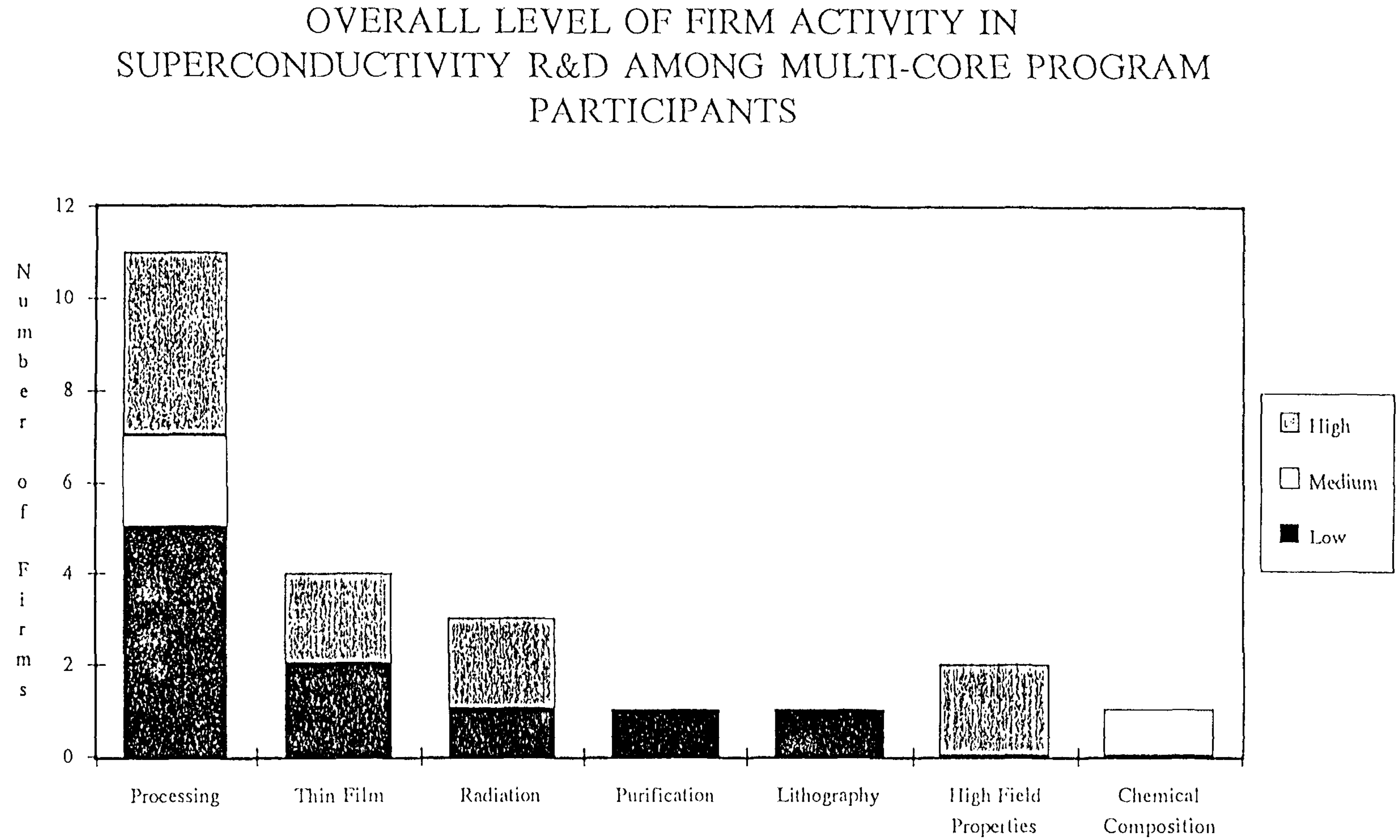


Figure 35. Mixture of Experienced with Inexperienced Firms in Multi-Core Program



### Complementarity

With diverse sectoral participation, one might also ask to what extent the programs are assisting in the creation of important complementary or supporting industries for HTS. Since the work is targeted at science rather than technology, one finds that it is difficult to predict where the important scientific complementarities lie that will also lead to complementarities in the market. Additionally, because industrial participation in many of the cores is rather thin, with only one or two participants, vertical or diagonal links with other firms are not likely to be significant.

It is possible, however, to get a rough sense of potential vertical complementarities by selecting the ISTEC divisions and Multi-Core cores that have two or more participants and dividing their affiliations between those that are primarily materials suppliers and those that are primarily systems or device developers. Figure 36 shows the proportion of suppliers versus users in the ISTEC program. The figure shows that the suppliers and users are well mixed in each of the divisions. The greater number of users participating in the project leads to a difference in number of participants, but this gap is not too different between divisions. The principle exception is the theory division which has more suppliers than users.

Figure 37 shows that in three of the Multi-Core cores, the split in participation is also roughly equal between these two groups: in the processing, thin film, and the radiation core, suppliers and developers show equal attendance.[104]

The possibilities of vertical relationships developing through these programs are thus present in each of these sections with two or more industrial participants. It is worth noting, however, that the types of research undertaken by these participants are quite similar and do not show a clear distinction between suppliers and developers. The stage of development of this field, again, appears too premature for clear linkages to arise in the division of research. Any relationships that may develop through the intermingling of these firms are probably not a direct result of their work in the program, but will only more indirectly arise through association.

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[104] Recall that the high field core primarily involves construction of the large magnets for future experiments.

Figure 36 Proportion of Supplier versus Users in ISTEC Program

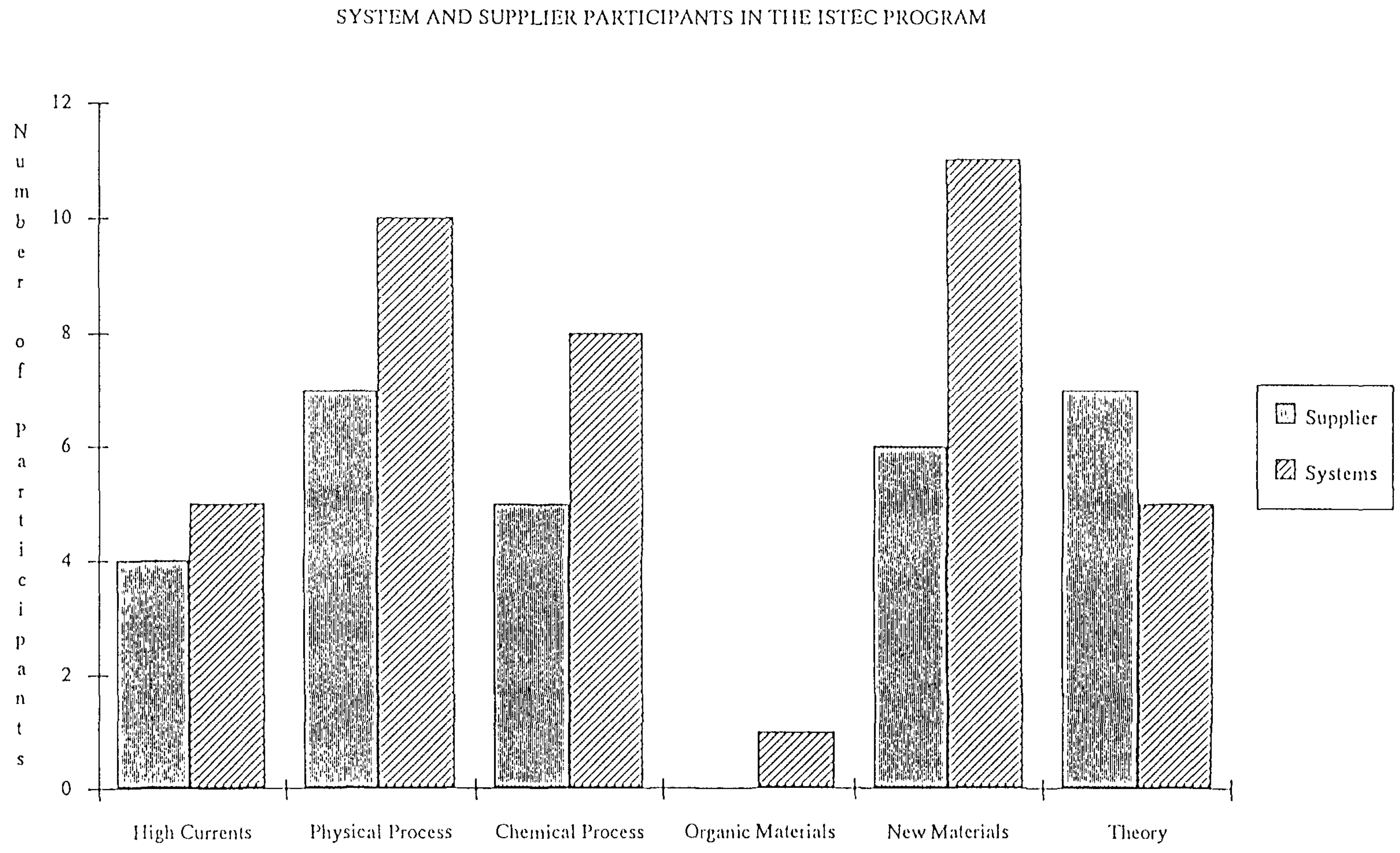
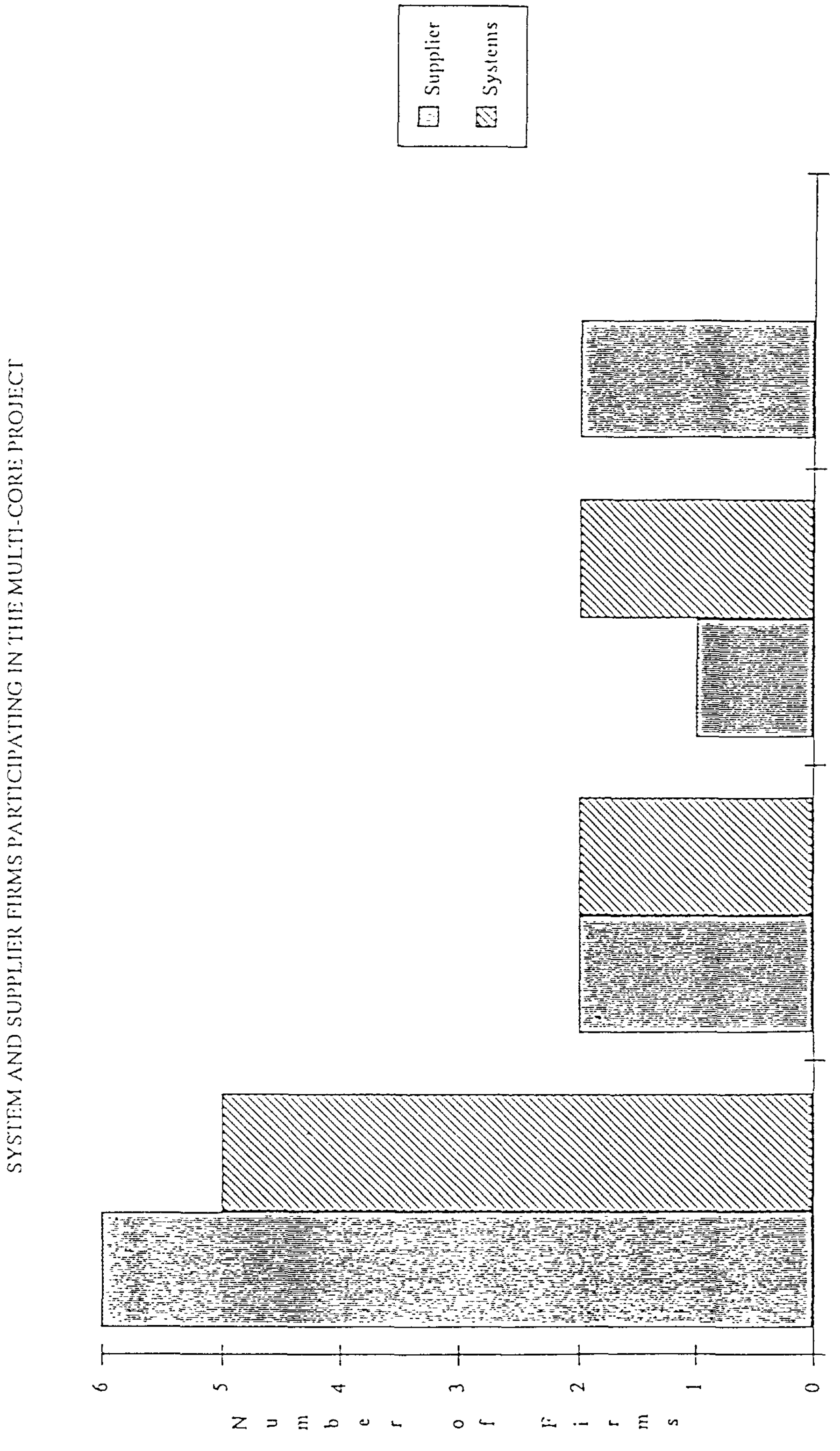


Figure 37 Proportion of Suppliers versus Users in the Multi-Core Program



### Diffusion

For many firms, particularly those just entering the field, the dispatching of a single researcher might mean the commitment of a large percentage of the organization's active HTS research team. Thus, unless the match between the interest of the firm and the research of the program is very complimentary, the opportunity costs can be high. For the majority of the research organizations interested in superconductivity this is the case. For these and other firms that do not find an ideal match with the research strengths of ISTEC or STA, the more pressing need was simply to keep up with developments in the field as the number of organizations conducting work world-wide was very large and the sense of the speed of the advance feverish in 1987.

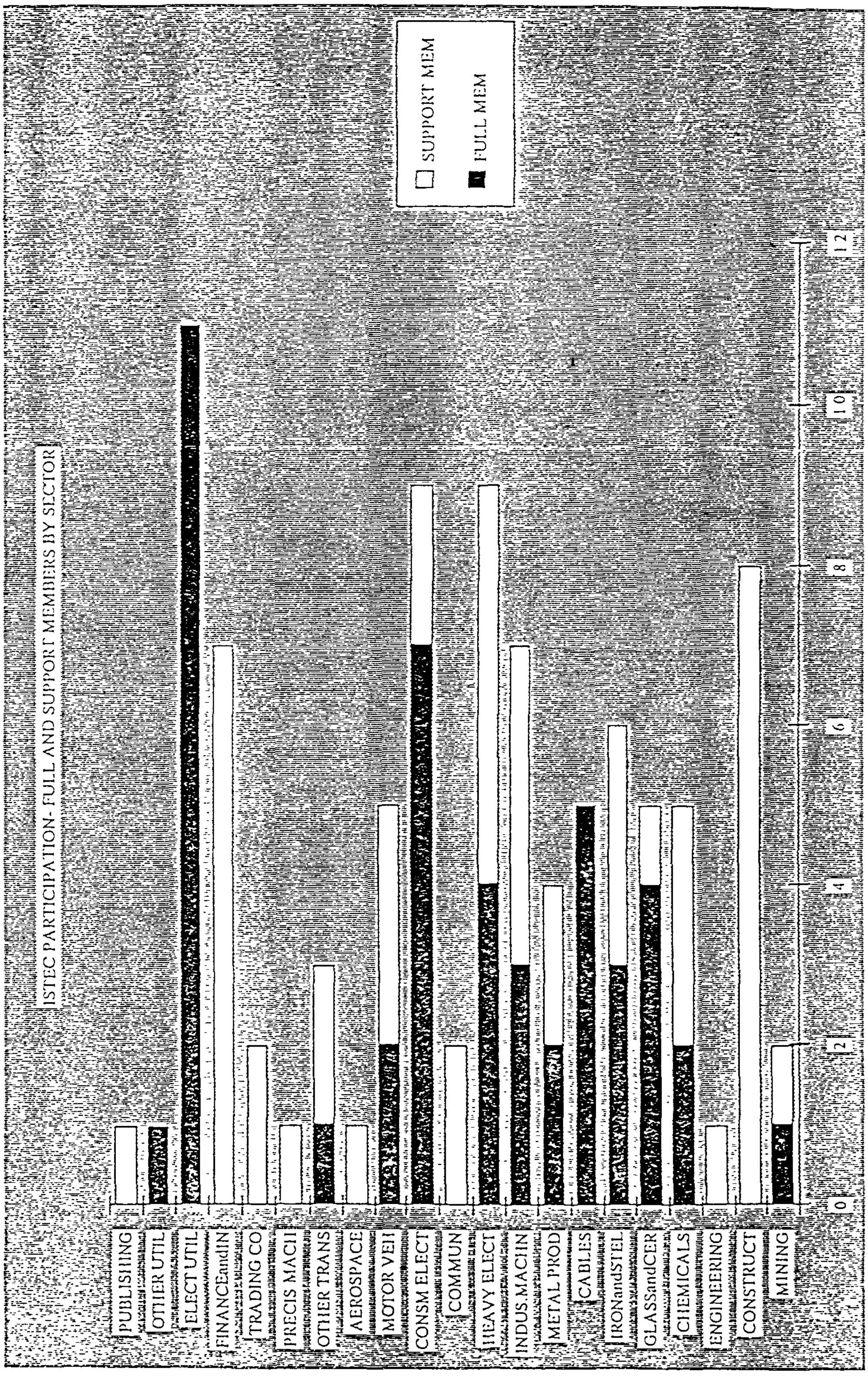
Thus both ISTEC and the STA have created supplemental activities to the research in order to promote the diffusion of information. In ISTEC, is it is the use of the less expensive Regular Memberships which provide access to information produced by the Center. In STA it is the New Superconducting Materials Forum.

Figure 38 shows full and regular member participation in ISTEC by sector. The full picture reveals participation by several different types of organizations. In the categories largely composed of regular members, there are firstly the financial firms mentioned earlier which appear primarily interested in the investment. A second type of firm, is the firm in a peripheral industry that could see significant benefits from the projects or technologies created by HTS. These include a conspicuously large number of construction firms and a couple of trading companies. And finally there are a spattering of firms which are potential users or support equipment developers in the categories of aerospace, motor vehicles, precision machinery, and engineering.

The Forum, with 148 member organizations, reaches an even wider audience. The Forum disseminates its information through a number of member activities which include a newsletter with articles reviewing research at various laboratories, workshops on specific themes such as current research on critical currents in bulk materials, and assists with the holding of larger symposia. Since its founding the Forum has held 16 workshops, with a typical attendance of 80, and 13 symposia, which typically attract 200 registrants.

Figure 39 shows the distribution of Forum members by industrial sectors. The figure shows that Forum membership is industrially diverse, covering 22 industrial sectors, with the single largest number of firms coming from the chemical industry, a sector slimily represented in ISTEC.

Figure 38 Sectoral Distribution of Full and Support Members in ISTEC



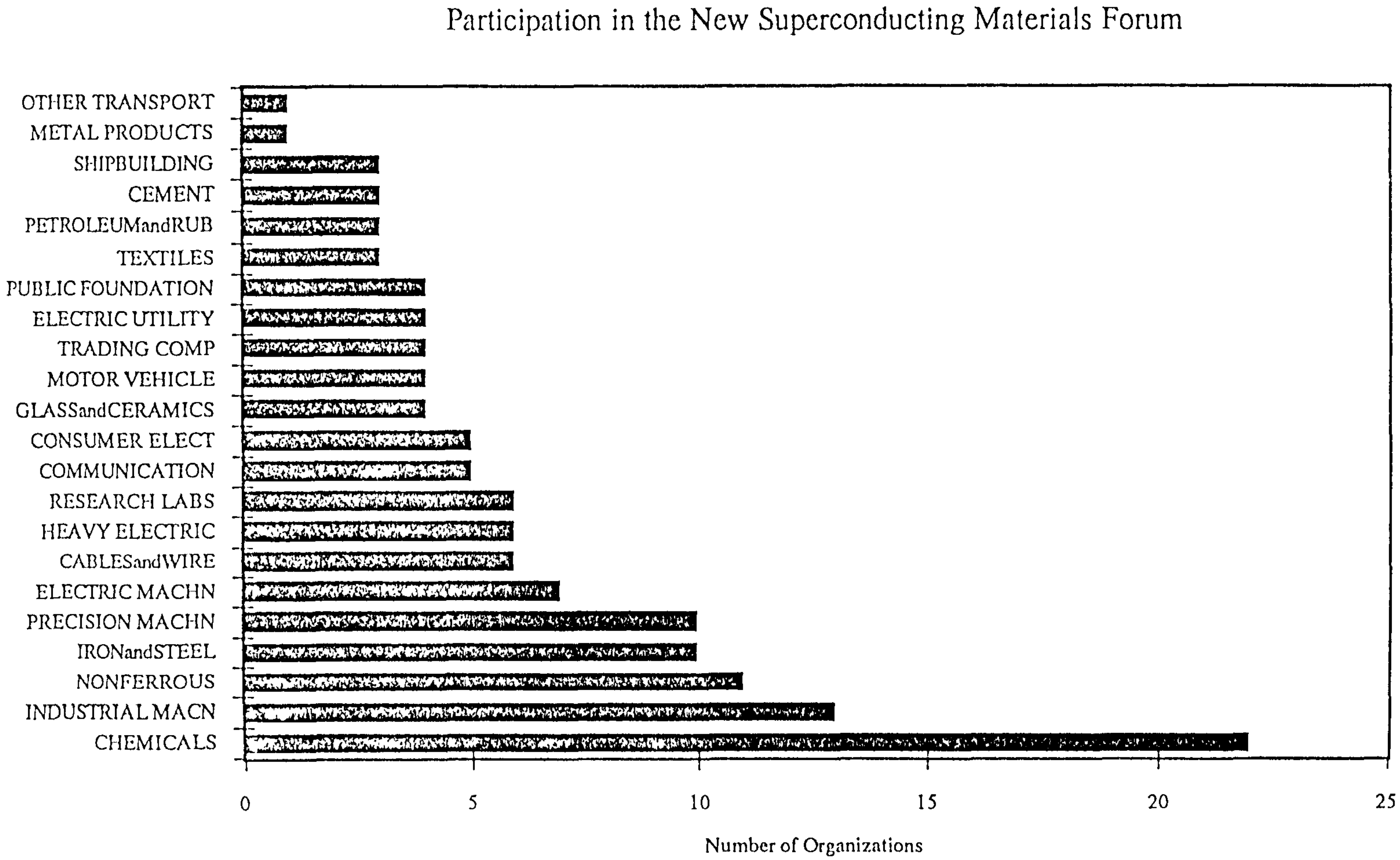


Figure 39 Sectoral Distribution of Superconductivity Forum Members

With much broader participation in the Forum than in the Multi-Core Program, it is not surprising that the Forum is perceived as the main activity and contribution to the industry of the Science and Technology Agency. In interviews with industrial representatives, questions about the value of the STA projects were usually responded to with answers regarding the Forum rather than the Multi-Core Program. Generally, industrialists gave the Forum a high rating noting that it has been an effective way of sorting out progress in this field, particularly in the first hectic year.

The combination of ISTEC and NSMF participation is shown in Figure 40. The figure shows that while there are some sectors in which firm participation in both programs is significant, such as iron and steel, motor vehicles, communication, and cable and wire, there are also sectors in which participation is very complementary, such as electric machinery, and many other in which one program was clearly preferred over the other. Firms in the finance and insurance sector, construction, engineering and the electric utilities are more highly represented in the MITI program and firms in the chemical, industrial machinery, precision machinery, nonferrous metal, textile, petroleum and rubber, and cement industries are more likely to be found in the STA Forum.

Finally we can ask to what degree these firms represent industry as a whole. In Figure 41 the number of patent applications by member firms is compared with the activity of all firms submitting two or more patent applications in superconductivity between January 1987 and June 1988. It is clear from this figure that participants represent the bulk of innovative activity in this field, which thus means that the information activities of the programs reach most of the organizations in the country that have significant programs in superconductivity.

Broad and extensive participation in the information activities of both the ISTEC and NSMF programs indicate that they are well set up to serve as efficient vehicles in the diffusion of scientific information. It is in this building of information networks that ISTEC and the Superconductivity Forum also provide a function not readily available in the market and provide an important contribution to innovation.

### Training

An important benefit being provided by both programs is one of researcher training. Firms are using both organizations as a means of educating its younger researchers in a new, fast moving field in which they almost uniformly have little experience.

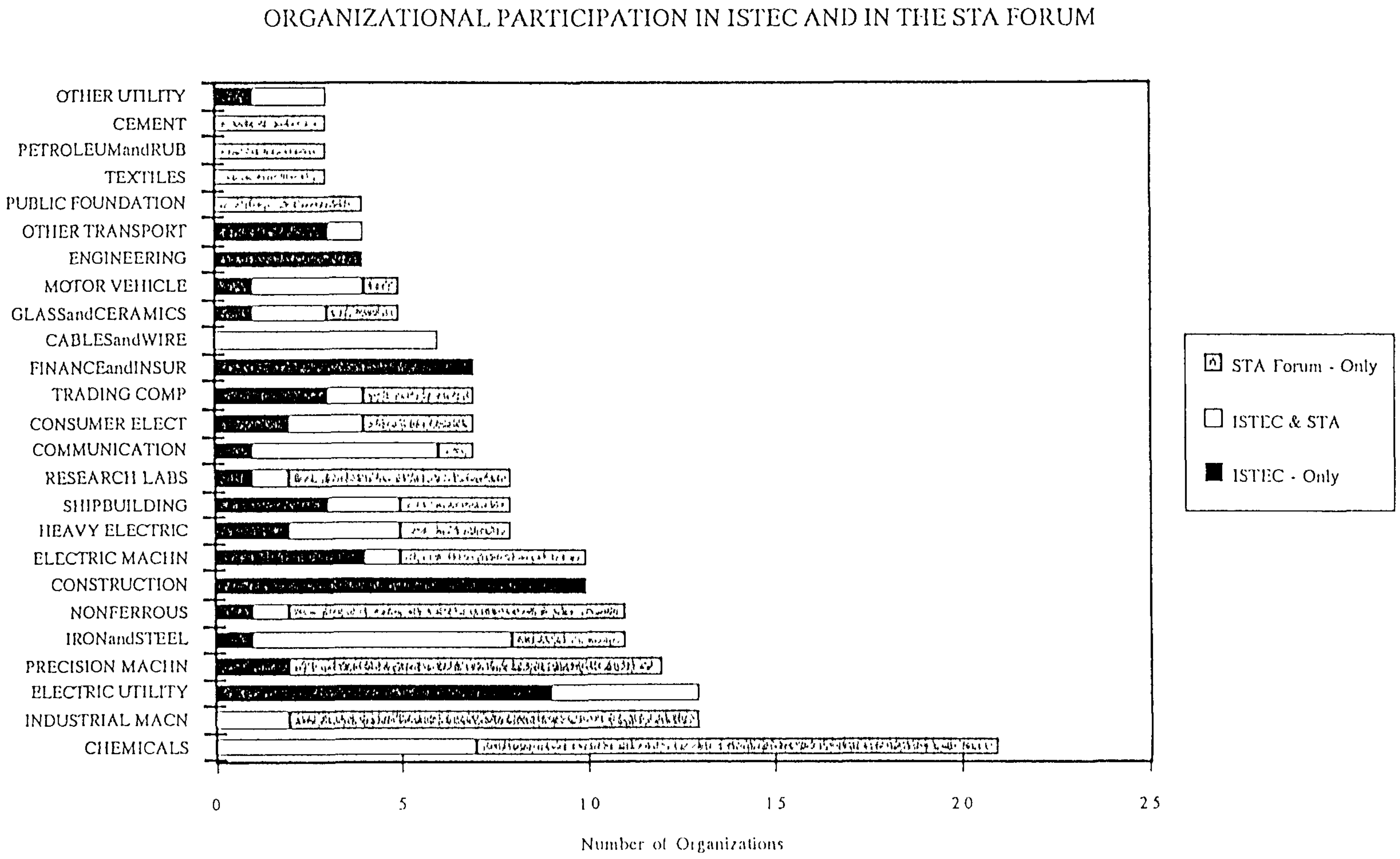
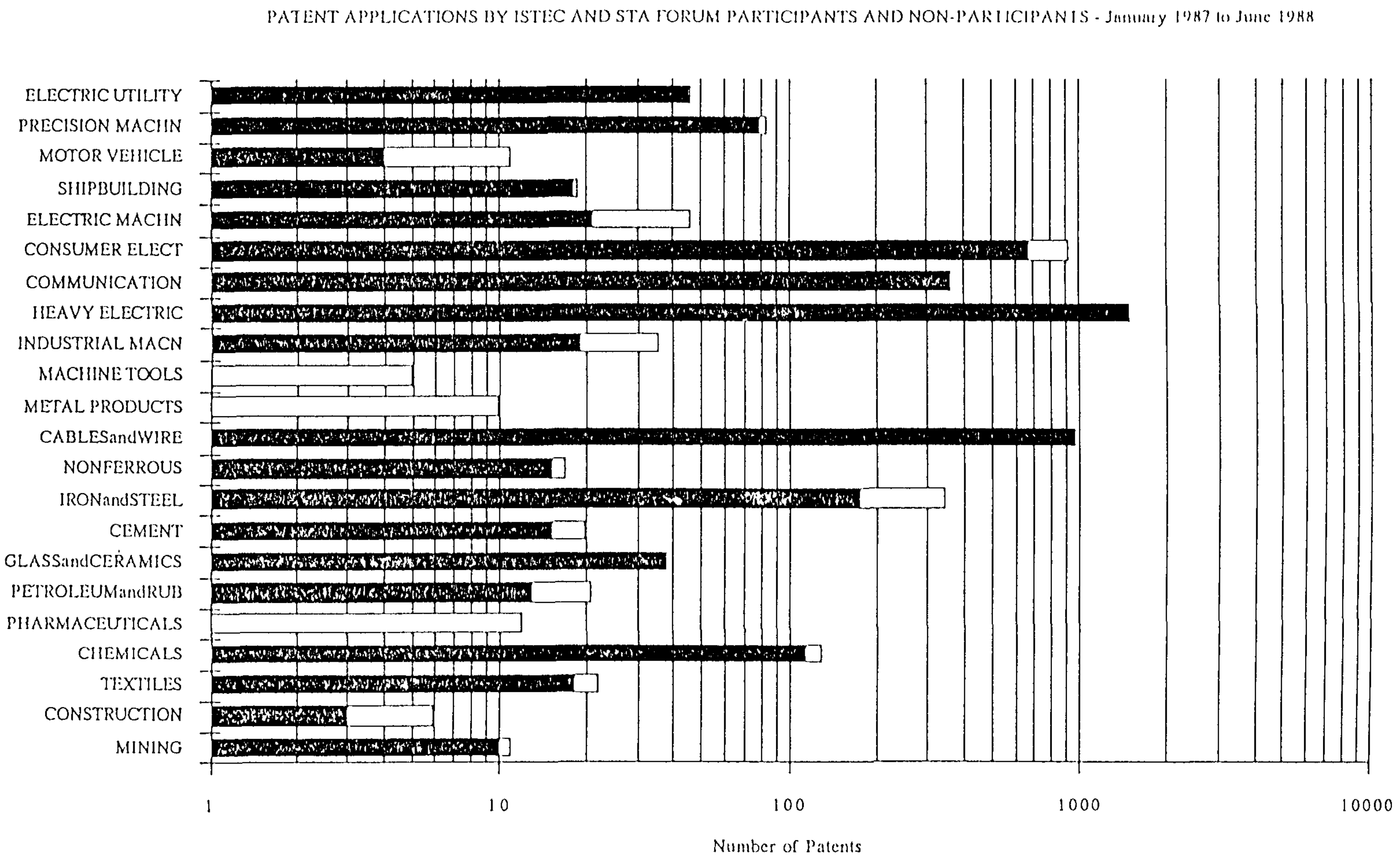


Figure 40 Combined ISTEC and NSMF Participation

Figure 41

Patent Applications of ISTEC and NSMF Participants in Superconductivity Compared with Industry Totals, January 1987 to June 1988



The age distribution of researchers dispatched to ISTEC is shown in Figure 42. The average age of these dispatched researchers is just over 30. Similarly, in the Multi-Core Program, laboratories reported that the common age of a firm's researcher was just under 30.

This training function of the laboratory is more clearly reflected in the degree backgrounds of the participants, for which ISTEC has provided data.[105] Figure 43 shows the highest degree taken by the researchers dispatched to the various divisions. Ph.D.'s account for 12 of the 77 researchers included in this survey, or 16% of the research staff, but master's level and bachelor's level researchers make up the bulk of the research talent, numbering 41 (53%) and 24 (31%) respectively. Prof. Tanaka has noted that many of these dispatched researchers are expected to use their work in an effort to gain a Ph.D. degree.[106]

The exchange is not just one way, however, as the laboratories in the Multi-Core Program effectively gain staff from participation. With the core researchers typically much older and more experienced than the dispatched researcher, it is common that the core will exercise some supervisory role over the dispatched researcher to assure that the research is directed toward problems of significance. Dr. Maeda of NRIM noted that all of the dispatched researchers who participate in the Basic Conductor core are treated like normal laboratory staff. They mingle, discuss their work, and submit themselves to virtually the same supervision as purely STA staff. Although university professors do not participate in the day to day grind of research at the core, their experience and advice can be a valuable contribution to the work of the laboratory and a good exchange for their access to the facilities.

## Concluding Points

This review of the ISTEC and Multi-Core projects provides us with the following conclusions about the mode of policy formation, the shape of the organization, and the role of the projects in innovation in the field.

1) MITI did not move "at the speed of light." In fact, it was the slowest of the bureaucracies to initiate work on an HTS R&D program. The lead in this field was in the private sector and the universities.

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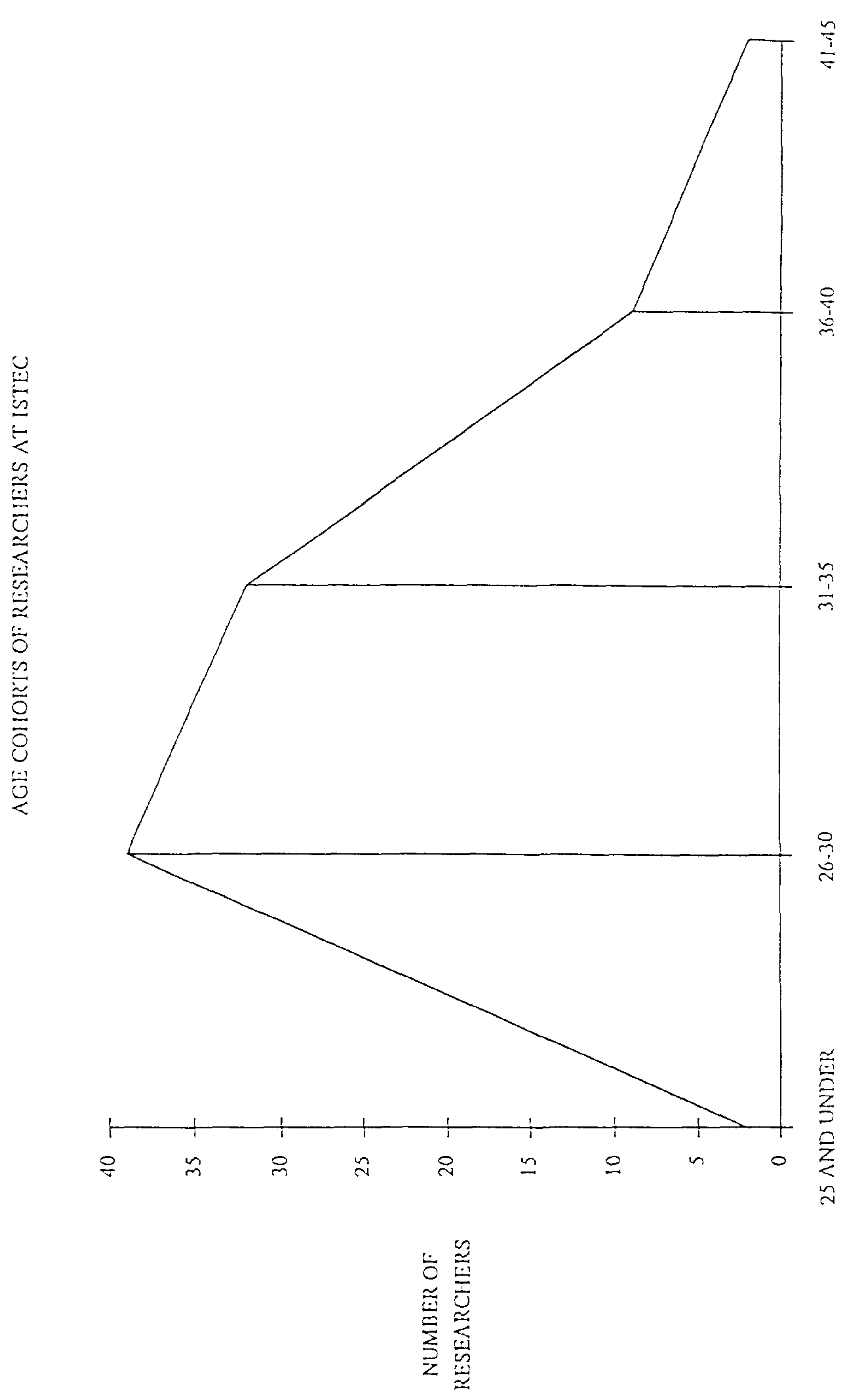
[105] This data was prepared by Mr. Nakagawa of the SRL and is dated April 5, 1990.

[106] "Looking Backward and Looking Forward at SRL," ISTEC Journal, Vol.2, No.4, 1987, p.17.

Figure 42 Age Cohorts of Researchers at ISTEC



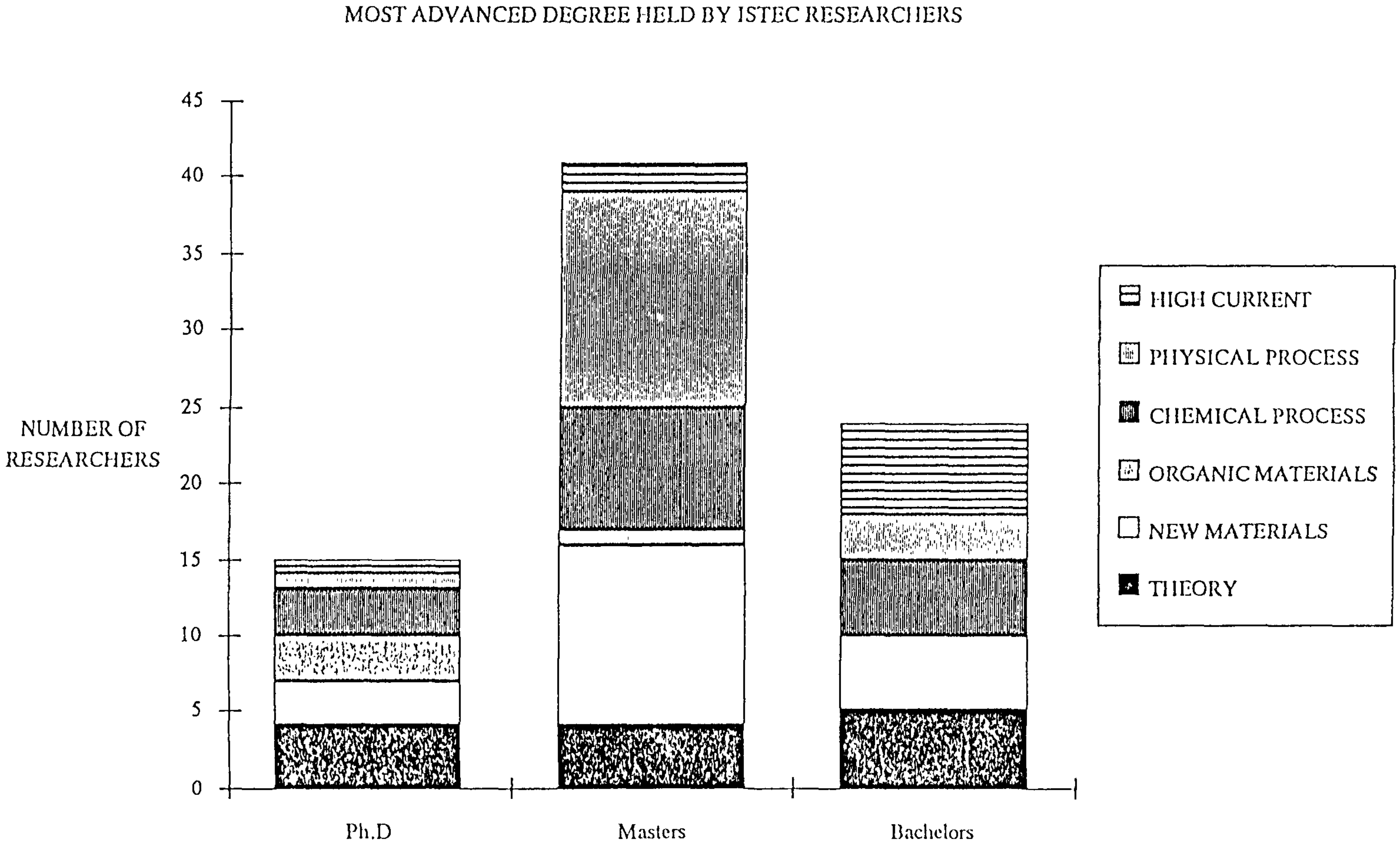


Figure 43 Degree Level of ISTEC Researchers

2) The rigidity of the national budget system was a primary cause of the shape of the government response. First, the budgeting system is rigidly defined and administered by the Ministry of Finance, and the system does not accommodate new discoveries in science. Second, as a result, money could not be obtained for research until the spring of 1988, almost a year and a half hence. Thus STA reacted by designing a program around existing facilities and MITI reacted by recruiting funds from the private sector in order to get work on a research center started.

3) Both programs manage participation by respecting the interests of the firms: cooperation is not assumed. The Multi-Core Program does not design for nor impose cooperation as its participants all engage in bilateral agreements with the hosting laboratory. In this program, the most popular core among firms reflect the strongest commercial relevance and the strongest reputation. ISTEC does expect cooperation, but achieves this and reduces conflict by dispersing potential competitors throughout the center.

4) The cooperative scheme is also a political one to gain support for funding. For MITI, industrial cooperation legitimizes its role in basic research, and for STA it shows industrial and scientific interest in developing a broad based program.

5) A major benefit to the science is in the equipment purchase and concentration of personnel. This is particularly true for the Multi-Core Program where some of the purchases will provide the laboratories with the best facilities in the world. Although this program is designed for five years, the equipment and opportunities for cooperation will continue, making program expiration a less significant issue.

6) Both programs are an aid to firm diversification. Because of the costs, ISTEC tends to assist larger firms, whereas smaller firms find the conditions of Multi-Core more accessible.

7) Information diffusion is an important part of both the MITI and STA efforts. For STA in particular, the New Superconducting Materials Forum reaches a broad audience, has been well received by the industry, and could be initiated soon after the HTS confirmation. It's role was seen as particularly valuably in the early days following the confirmation when many new actors were joining and many rumors of progress were afloat.

8) Participation patterns indicate that both programs may lead to the formation of inter-firm complementary linkages, but progress is too early to tell.

9) Finally, training is a very important function of both programs, and is the main benefit being received by the companies.

If these programs can provide U.S. policymakers with one general lesson, it is that the Japanese science policy machine operates with many constraints, and even in "basic" research, the tension between cooperation and appropriation must be carefully managed.

### - *The Challenge of Continued Support*

Finally, although both ISTEC and the Multi-Core programs are designed as multi-year activities, they must still compete for funding every fiscal year, and must therefore must work hard to maintain public and political support should the frequency of breakthroughs subside. For example, with the passing of the initial excitement over HTS, bureaucrats from other programs in STA began chipping away at the planned Multi-Core budget. Other issues, such as the environment, moved in to receive higher priority and funds for HTS began to leak out. The budget for 1990 turned out to be 34% less than initially planned, and for 1991, 24% less than planned in 1991.[107]

To continue to receive strong funding support, the collective activities need to show progress. However progress in the eyes of the government and the public is quite different from progress in the minds of the firms. Whereas the participants in ISTEC and Multi-Core are interested in speeding the advance of the technology for commercial application, the dreams of the public form around a more vague image of a society floating on room temperature superconducting devices. Thus, whereas firms tend to emphasize the penetration of practical barriers to near-term use, such as current limitations, these are not measures which the public readily comprehends. The public is stimulated by temperature.

Prof. Tanaka appears well aware of the political importance of increasing the critical temperature of these materials. When Dr. Yamauchi, the Director of Division 2, noted at the annual review meeting that he was hoping to achieve a critical temperature of 130 K through their research, Prof. Tanaka's response was "Awfully low, isn't it? ... You must exceed 150 K."[108]

In the absence of temperature breakthroughs, the programs can gain some media attention with flashy announcements of new developments, such as having goldfish

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[107] The initial five year plan for the Multi-Core Program called for a budget of 4.116 billion yen in 1990 and 3.260 billion yen in 1991. The amounts actually allocated were 2.733 billion yen in 1990 and 2.480 billion yen in 1991. (Data from Multi-Core Program planning office, STA.

[108] This is not to imply that there are not technical hopes in such an advance as well. Prof. Tanaka has commented that "... there is no doubt that the essence of high temperature superconductivity becomes clearer as temperature rises." "Looking Backward and Looking Forward at SRL," op. cit., p.11.

floating above a newly developed magnet, or having Prof. Tanaka floating above a newly developed magnet, but these only act as temporary reprieves. To maintain funding, they will have to show some progress. Despite the current rhetoric about wanting to support basic research in Japan, there is competition for funds and the system tries to fill black holes.

## VII. SYSTEMS AND DEVICE APPROACHES

When we move away from projects that are primarily based in the science, to those involving the development of technologies, we might ask whether the forms of cooperative R&D projects or their roles in innovation change. In this section we will explore this question through the example of five government promoted R&D projects that incorporate the use of superconducting materials. Three of the projects are directed toward the development of specific superconducting devices: Josephson junctions, high temperature superconducting electron devices (HTS-ED), and a technology known as a quantum flux parametron (QFP). The other two projects are targeted toward the development of prototype system technologies, of which superconductors play an integral part. The systems technologies are the superconducting electric generator and an advanced version of a high sensitivity superconducting sensor system known as a magnetoencephalograph.

Why attempt to distinguish between systems and devices? These are separated primarily for the analysis of collaboration. The division is based on a hypothesis that the different technical requirements will lead to different forms of collaboration, and perhaps different outcomes. Devices will tend to be technologies that can be developed and appropriated within a firm and which will eventually be produced largely by a single firm. Firms would like to, and will, have the ability to appropriate their advances in the technology. The participants will likely be competitors. Systems, by contrast, will tend to require the skills of a number of firms from different sectors. Thus there are more likely to be complementary linkages between these firms, with fewer competitive barriers to collaboration than in the device programs. Thus a question that will be considered in this section is how policy and management directed toward systems and devices differs, and how both differ from that of science.

These five programs present us with a range of technological and organizational variety. They represent technologies in which Japan was clearly trying to catch up to the international lead, and devices in which it may well be the leader. They represent discreet devices, small systems, and large systems. And they represent projects directed under five different parts of the Japanese bureaucracy. How might these and other variables affect the performance of the R&D? This will be explored in the discussion below.

## Brief Introduction of the Programs

Before discussing the role and management of the government programs, I will give a brief introduction to the programs, the technologies, and reasons for pursuing development.

### - *Josephson Junction*

The first of the device centered projects to be started was the Josephson Junction project which got underway in 1981. This research is one part of a much larger program to develop a future generation of supercomputer, the *Kagaku Gijutsuyo Kosokukei Keisan Shisutemu*, which was funded through MITI's Large Scale National Projects office. The overall goal of the supercomputer program was to develop an integrated computer system that would meet the high speed computational needs of science. These needs would include data processing of satellite images, plasma simulation for nuclear fusion, numerical weather analysis, aerodynamic simulations for aircraft, and molecular science.

The program was initiated in October of 1981 and was scheduled for 9 years with a total budget of about 23 billion yen. Although official figures for the Josephson junction portion of the project were not released, sources indicate that it was on the order of 250-300 million yen per year, or about 10% of the overall project budget.

Primary technical themes in this program were 1) the development of high speed devices that can exceed the performance of current silicon-based semiconductors, 2) the development of parallel processing systems, and 3) the development of parallel processing software. The Josephson junctions were selected as one of three technologies that might provide higher performance through higher speeds.

In addition to the Josephson junction, program researchers investigated High Electron Mobility Transistor (HEMT) devices and Galium Arsenide Field Effect Transistor (GaAs FET) devices. All of these devices are of interest because they provide the possibility of processing information at very high speeds with low energy losses. Of the three, the Josephson junction appears to offer the best stand-alone performance as shown in Figure 44. How this is done is briefly introduced below.

As most observers of technology are aware, computers process information digitally. The essence of this digital processing is a binary code, a series of ones and

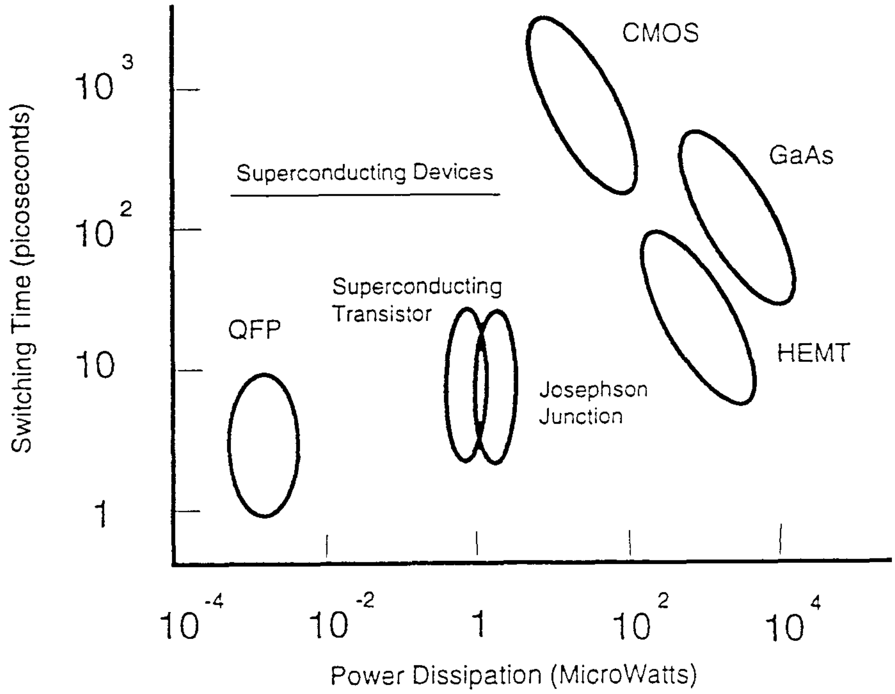

Figure 44 Performance of Various Computer Switching Devices

(Based on Figure 2 in Yasutsugu Takeda, "Prospects for Superconducting Electronics," First International Symposium on Superconductivity, August 28-31, 1988, Nagoya, Japan.)

zeros, which the computer must group and process to represent the information that we desire. The faster the computer can process these ones and zeros, the faster our information can be manipulated.

In the computer, these ones and zeros are represented by different levels of resistance in a semiconductor. Each time a voltage is applied, these levels will change. Thus the speed at which the semiconductor can switch between these two states is an important factor determining of the computing power of the computer. We would like to process as many of these binary bits of information as possible.

The Josephson junction is attractive as a technological option because of the theoretical possibilities of 1) increasing the speed of the switch and 2) decreasing the distance between switches through which a signal must travel. First let's examine this characteristic of switching speed.

The Josephson junction works by taking advantage of an effect first proposed by Brian Josephson when he was a graduate student at the University of Cambridge in 1962. Josephson theorized that it was possible for a current of superconducting electron pairs to tunnel through an insulating layer separating two superconductors while maintaining the phase coherence of the pairs' wave functions on both sides of the insulator. For this work Josephson received the Nobel prize in 1973.

In effect, Josephson predicted that a superconducting current could pass through an insulator without the need of a voltage to drive this current. This effect is, however, very sensitive to magnetic fields and a small magnetic field can cause the junction to break down, creating a voltage across the insulating layer. The switch between the presence or absence of a voltage, which occurs on the order of a few picoseconds (trillionths of a second), can be used to represent the binary 1 and 0 states used by the computer.

The switches must then be integrated into a system for the phenomena to be of practical use in a computer, and this is where a second theoretical advantage of this technology arises. In conventional computer, somewhere on the order of 40% of the cycle time is estimated to be lost from wiring delays.[109] But as the electronic signal itself is already traveling near the speed of light, the challenge is in decreasing the distance between the switching devices. Today's fastest semiconductor computers, for example, operate on the scale of nanoseconds. As light can only travel about a foot in a nanosecond, this means that a tremendous amount of signal manipulation must occur over a very short space. Computers that would operate faster than a nanosecond, would have to be only a few centimeters on a side, or about the size of a tea cup.[110]

However, recall that the semiconductor devices achieve their effect by varying resistances. This means that waste heat is generated in the switching process. If too many of these switches are packed too closely together, the emitted heat is enough to cause the switches to malfunction or to melt. Because a Josephson computer would rely on entirely different switching phenomena, the level of waste heat generation would be much lower. In 1980, Juri Matisoo estimated that a Josephson computer would have operating voltages that were smaller by a factor of 1,000 and currents smaller by a factor of 10 when compared with semiconducting computer.[111] Thus the level of waste heat is four times

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[109] Hisao Hayakawa, "Josephson Computer Technology," Physics Today, March 1986, pp. 46-62 (48).

[110] Randy Simon and Andrew Smith, Superconductors, New York:Plenum Press, 1988, p. 177.

[111] Juri Matisoo, "The Superconducting Computer," Scientific American, May 1980, pp.38-53 (47).

lower than that of semiconductor devices, allowing for a much denser packaging of the switches and hence a higher system speed.

Finally, in addition to these principal advantages of speed and low heat generation, Josephson junctions provide other advantages that arise from its superconducting property.[112] Strip lines and superconducting ground planes in the chip allow the transmission of high frequency signals at minimal loss or distortion - a result that is difficult to achieve in semiconductor circuits. Secondly, because superconductors are insensitive to impurities and crystal imperfections, sufficient uniformity can be achieved, at least in theory, to allow the fabrication of Josephson devices on the scale of an entire wafer or in three dimensions.

### - *Goto - Quantum Flux Parametron*

The Quantum Flux Parametron is a switching device which has the theoretical possibility of significantly increasing the speed and power of computers well beyond the performance of both semiconductor technologies and Josephson junctions. The device provides for very fast switching times, on the order of a picosecond, and very low power dissipation, a million times lower than silicon semiconductors, which could both contribute to achieving computers with TeraFlop speeds.[113] A comparison of the switching time and power dissipation of this device is also shown in Figure 44.

The QFP is basically a circuit that is composed of twin Josephson junctions and two exciting inductances shunted by a load inductance.[114] This is shown in Figure 45. The trapping of the quantum flux in one or the other of these loops represents the logical states of the circuit. This design allows signals to be processed without physical contact with the surrounding medium.

In addition to the speed and power dissipation advantages over the Josephson junction, the QFP can be designed as a three-terminal device through the use of coupling inductors, and the circuit can amplify signals through a latching action. This makes the QFP appropriate for both pipe-line and parallel computer architectures that would provide a very fast processor system.

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[112] Hisao Hayakawa, p. 47.

[113] "Chodendo Su-pa-kon ni Michi," Nikkei Sangyo Shimbun, September 29, 1990.

[114] Eiichi Goto, et.al., Fluxoid Josephson Computer Technology, Singapore: World Scientific, 1988, p. vii.

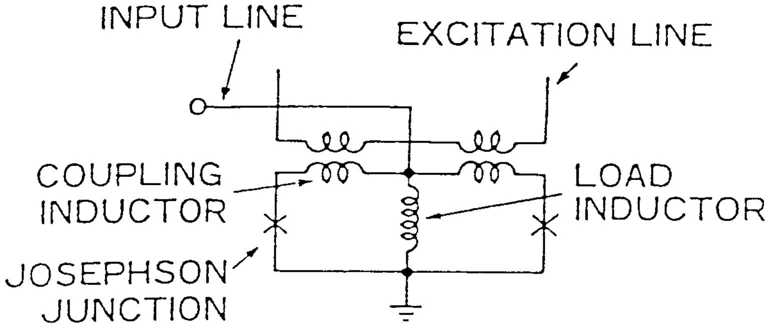

Figure 45 Schematic of the Quantum Flux Paramatron

(From Yasutsugu Takeda, "Prospects for Superconducting Electronics," First International Symposium on Superconductivity, August 28-31, 1988, Nagoya, Japan.)

- *HTS - Electron Devices*

When MITI petitioned the Ministry of Finance for funds to initiate R&D programs in high temperature superconductivity, it did so with two agendas. The first was to provide funds to ISTEC to support its research in the fundamental development of the material. The second was to support a project which would immediately look for device applications of these new materials. It is this second project, termed the High-Temperature Superconducting Electron Device (HTS-ED)Project, that is described here.

The HTS-ED project involves six firms and the ETL, and has a projected budget of 25 billion over its planned 10-year life (1988-1997).

The overall technical goal of this project is to search for and develop signal processing devices using the new high temperature materials. The six projects eventually selected are two proximity effect devices - a field effect type and a charge effect type; two superconductor base devices - a low-energy injection type and a high-energy injection type; and two "new-functional" devices - single electron tunneling and localized state tunneling.[115]

In the proximity effect devices, the electron pairs which give rise to superconductivity are used as the carrier. The source and drain are made from the HTS materials with a semiconducting material layered in between. In the field effect design, an electric field induced by the gate voltage controls the current of electron pairs. In the charge injection design, quasi-particles are injected into the gate semiconductor to change the gap-width which controls the electron-pair current.

In the superconducting base devices, the quasi-particles injected by an emitter are used as the carriers. In the low energy design, the injection energy is approximately equal to the barrier height between the emitter and base, which provides the advantage of low power consumption. In the high energy design, the injection energy is several times larger than that of the barrier height,m and a ballistic effect is expected to substantially improve gate efficiency.

Finally there are the two new-functional devices. The single electron transistor, or SET, takes advantage of a very thin superconductor-insulator-superconductor structure to create a secondary-quantum macroscopic effect similar to the Josephson effect. Two SETs would be combined to make a three terminal device. The localized state tunneling device relies on the formation of various energy levels in the insulator. Quasi-particles injected from the source will jump to the localized state when the gate voltage is applied and will jump to the drain when the voltage is removed. As no relaxation loss exists in the gate channel, this device has a higher theoretical speed.

### - *Superconducting Electricity Generator*

In a land where 99.7% of the petroleum, 95% of the natural gas, and 90 % of the coal is imported, and where the government is facing increasing resistance to the implementation of its plan to increase nuclear power generation by 100% in 10 years, the efficient use of energy is an issue of continuing policy priority.

Aggravating the lack of energy resources is the increasing growth in energy demand, particularly electric energy. During the decade following the 1973 oil crisis,

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[115] The description of the HTS devices draws heavily on a program overview provided in Tadashi Ikeda, "Introduction of High-Temperature Superconductivity Electron Devices Process," Extended abstracts of the 8th Symposium on Future Electron Devices, October 30-31, 1989, pp. 237-240.

energy demand in Japan was essentially flat, with an average annual increase of 0.1%. However, during this same period, electricity consumption increased an average of 2.8% per year. Since 1983, the increase in electricity consumption has continued to increase steadily, reaching 5% per year at the time of the start of the Super GM project in 1987. In this year, Japan's electric power plants had a capacity of 163 GM, producing 640 TWh of electricity.

The superconducting generator offers one possibility of improving the efficiency of the generation of electricity through reduced losses in the generator's electromagnetic system.

The Superconducting Electric Power Generator program, known as Super-GM, is the latest and largest of a series of government and utility sponsored projects to develop a superconducting electric power system. The primary goal of this project is to develop and demonstrate prototype superconducting electric generator systems which would be rated at a power output of 70 MVA, with the expectation of continued development of a 200 kVA prototype to follow the project's completion.

The project is being funded by the government through the New Energy and Industry Development Organization (NEDO), for an eight year period with a planned budget of 25 billion yen.

How does the superconducting generator work?

In conventional generators, the copper is typically used in the conductors and iron cores are employed to generate the magnetic flux. However copper has a finite resistivity, even when cooled to very low temperatures, and this limits the current density of electricity transmission (about 8 A/mm$^2$). In the Super GM project, these copper windings will be replaced by superconducting Niobium Titanium filaments which offer the attraction of higher current density ($J_c = 10^2 - 10^3$ A/mm$^2$), higher critical fields, and without cores, can produce much higher magnetic flux densities than those of the saturation magnetization, $B_s$, of ferromagnetic materials.

In using superconductors, it is estimated that the generating loss will be reduced by 60% as a result of the disappearance of the field winding loss and the reduction of mechanical and stray losses.

However, the absolute value of the improvement is not large. Conventional generators have achieved efficiency levels of 98.7%, so a 60% reduction in loss would only bring a 0.78% absolute increase in efficiency. Given the large size of utility generators, this small improvement is still estimated to save about 600 million¥/year in a 1 GW plant. For the national system as a whole, a one percent savings is roughly equivalent to the power output of a 1 GW power station.

Nonetheless, even advocates of the system will admit that the efficiency gains are not in themselves sufficient reason to develop the superconducting generator. As K. Aiyama of MITI's Electrotechnical Laboratory has pointed out, "Even if their (generators) SC-rization ("superconductorization") could reduce these losses by half, the incentives for their SC-rization cannot be very high only with the loss reduction. The new functions or the advanced performances of the superconducting apparatus in the system are desired...."[116]

Some of these benefits to the cost performance of the generator will stem from greater system stability, smaller size, and reduced weight. Superconducting power systems with long distance transmission lines can provide increased stability which leads to increased transmission capacity. For example, a 40% increase in system stability can lead to a 40% increase in transmission capacity. This is because the capacity of the transmission line is not determined by a thermal limit, but by system stability. In practice it is estimated that a 10-60% savings in transmission facilities can be achieved.[117]

Secondly, the smaller size made possible by the use of superconductivity will reduce the manufacturing cost of the system by about 10%, even given the higher costs of the NbTi filaments. And thirdly, the generator itself is expected to be 40% lighter than conventional generators. Advocates admit, however, that the savings may be offset by the complexity of the designs.

The long-term goal of proponents of this technology, however, does not end with generator development, but envisions a complete electricity transmission system with superconducting components. This would mean the use of superconducting materials in the transmission line, the transformers, and the armature of the generator.

What utilities would like to do is both increase the utilization factor of their equipment and to reduce the losses in operation. The average utilization factor was 45% (76% nuclear, 41% thermal, and 24% hydraulic) in 1987. For the nine major utilities (accounting for 87% of the nation's electricity supply) Aiyama estimates that the loss rate, (defined as (1- electricity sold/electricity generated)*100) was 9.6%. He estimates that the absolute value of this loss can be reduced by 4% with a fully superconducting system.[118]

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[116] K. Aiyama, "Application for Superconductivity to Power Systems," presented at the 2nd International Symposium on Superconductivity (ISS'89), November 14-17, 1989, Tsukuba, Japan, pp.1035-1040.

[117] K. Aiyama, op.cit.

[118] K. Aiyama, op.cit.

However, these components operate with alternating currents rather than the direct currents which pass through the rotor, and the state of alternating current superconducting wire is still relatively primitive.

Through a fully superconducting system, the unit capacities of the apparatus in the system are anticipated to increase both as power capacities are increased and as the mechanical or transport constraints are relieved. Higher power density cables, for example, would increase the transmission capacity of the system. In addition, the more compact size of the superconducting apparatus in the system is argued to be attractive for crowded areas, where the room for new transformers and control stations is extremely limited.

- *Superconducting Sensor*

The Superconducting Sensor project is directed at the development of an advanced magnetic imaging system, known as a magnetoencephalograph, for the diagnosis and study of the human brain. Through a network of extremely sensitive sensors, the plan is to develop a prototype system that can follow the paths of neural nerve impulses.

Under the auspices of the Key Technology Center, a project was initiated at the end of fiscal year 1989 which was aimed at the development of sensor technology that exploited the properties of superconductivity. The Superconducting Sensor Laboratory (SSL) was formally opened on March 23, 1990, and is planned for operation until the end of March 1996. The total budget for the program is 5.7 billion yen, 70% of which is provided by the Key Technology Center and 30% of which is provided by the participating firms. Unlike the other programs reviewed here, the Key Technology Center does not provide research grants to existing organizations, but invests in an independently incorporated research corporation.

The magnetic imaging system uses sensors, known as SQUIDs (Superconducting Quantum Interference Devices), that can measure extremely tiny magnetic field changes. SQUIDs have been used in a range of applications such as in geophysics - in magnetotellurics, rock magnetism to search, for example, for ore deposits, and paleomagnetism; in gravity wave detectors; and in biomagnetism - to detect eye movements, fields generated by the heart and brain, eye movements, and nerve impulses.

Although the first single channel SQUID devices for magnetoencephalography were developed in 1976 by Biomagnetic Technologies Inc. of the U.S., it was not until the mid-1980's that firms in Japan took a significant interest in its development.

How does this work? SQUIDs are essentially superconducting loops that take advantage of flux quantization to function as magnetic sensors. First consider the SQUID as a superconducting ring that serves as a storage device for magnetic flux. Weak links most often in the form of Josephson junctions, are built into this ring to allow the level of magnetic flux to change. Now, physics tell us that this magnetic flux in the ring can only take on discreet flux quanta, so discreet levels of current flow in the ring to maintain the appropriate level of flux when the ring is placed in a magnetic field.

When a magnetic field is applied to the ring, a current is induced which tries to oppose any change in flux level. However, when this current exceeds the value which the Josephson Junction can manage, the weak link temporarily fails, allowing additional magnetic flux into the ring. After allowing the flux quanta into the ring, the Josephson junction can resume normal operation.

To make this a sensitive magnetic sensor, the current that flows through the weak link is measured by using a feedback current that just cancels the current induced by the magnetic field. This makes it possible to determine the strength of the magnetic field at levels on the order of a thousandth of a flux quantum smaller than that stored in the SQUID ring.

In practice, the SQUIDs are used by the magnetoencephalograph to take images of the body in specific locations and at specific times. With the early devices this was accomplished by taking measurements serially over small intervals of time. As a result the data gathering could take hours to complete, by which time the metabolic conditions of the patients could be quite different. Current devices commonly use two sensor clusters to get symmetrical measurements of the two halves of the brain. In state-of-the-art devices, each of these clusters has about seven channels each which take the magnetic measurements. To increase the accuracy of the imaging the and to shorten time required to take an image, one would thus desire a greater number of sensors to pick up the magnetic movements, and this would require more channels.

In summary, the overall purpose of this Superconducting Sensor project is to develop a magnetic imaging device that would be far more accurate than current equipment, and which would eventually allow the imaging of the processes of information management within the brain.

## Dimensions of Comparison

### Who motivated the project

In our earlier discussion of science-based projects in HTS, we examined the question of project formation and found that the government is poorly set up to accommodate the funding of an unexpected breakthrough in science. MITI was not seen to jump into the lead, but was prodded by the industry and the scientific community and its ability to direct new funds to this activity was largely restricted by the rigidity of the government funding process. The only agency in which it appears that the bureaucrats took the lead was STA. But their response seemed to be as much to protect their turf as it was to promote the science. The initial policy lead was varied.

However, this was an exception in government promoted cooperative R&D as it was in response to a major, unanticipated event in science. The cases in this section are more typical of the project formation process. Again, the principal questions are who takes the lead, how are the technologies identified, and how are the programs formed.

The principal thesis of this section is that relative technological advance is an important determinant of the changing government role in research and development. Although part of the change in the government's role is because of the greater strength of the firms, strong firms can still exist in stagnant markets. It is the speed, scale, complexity and uncertainty of technological change which more strongly influences how the government will respond.

When Japan lagged the west, the targets were clear and the setting of a research agenda relatively straightforward: target the west. However, when Japan catches up the targets disappear and when technology is advancing rapidly on a broad range of fronts, uncertainty greatly increases about which option are best or which even exist. As MITI bureaucrats rotate their positions every two years, often to very different parts of the Ministry, accumulating meaningful technical expertise is impossible.

As a consequence, MITI has to increasingly draw on a broader net of outside expertise for new ideas for research, and consequently distances itself from setting the technological agenda.

These variations in government involvement can be seen in the five cases reviewed here. In the cases of the Josephson junction project and the superconducting generator project, the targets were generally defined by advances overseas. In the advanced sensor project the technology ultimately chosen was the superconducting sensor, but this was only after a lengthy study of a large number of sensor options, a process in which MITI was principally an observer. Similarly in the case of the HTS electron devices project, MITI solicited proposals for specific ideas to promote this general theme.

Although the Goto-QFP project falls under STA rather than MITI, its formation also reflects the same dependence of the bureaucracy on outside ideas when they are chasing the frontier.

First the formation of the Josephson junction project and the Super GM project will be described, with this being followed by the superconducting sensor, HTS electron devices, and the Goto-QFP project.

### - *Josephson Junction*

Although the Josephson junction project was formally presented as one alternative for fast switching to be investigated along with High Electron Mobility Transistors (HEMT) and Galium Arsenide semiconductors, the target of this task was clear: IBM. The decision to pursue Josephson junctions was an extension of an obsession with overcoming IBM that had been a part of government policy and company strategy for over a decade and a half.[119] And that target made the decision to pursue Josephson Junction technologies a more straightforward one for MITI. As an example of the preoccupation with IBM, while Takuma Yamamoto was President of Fujitsu, he annually greeted his company's new employees by encouraging them to all work together to overcome IBM's world dominance.

Since 1965, IBM had been supporting a substantial amount of research into the possibility of a superconducting computer which would exploit Josephson junctions. Over 15 years, it is estimated that over $100 million was invested in this project, and at its peak some estimated that as many as 115 to 140 researchers were involved.[120] The first director of the IBM project, Juri Matisoo, noted that they were attracted to this technology because of 1) the ability to be switched quickly between two states, 2) the low power consumption, and 3) evidence of "gain," or amplification of the signal.[121]

As IBM's advances in this technology were more appreciated, interest in Japan began to pick up in firms in the early 1970's. Before this time, Josephson junctions were considered a relatively obscure phenomena with research activity centered in the universities. The leading academic research activities were being directed by Professors

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[119] Marie Ancherdochy, op. cit.

[120] Randy Simon and Andrew Smith, p. 179.; Arthur Robinson, "New Superconductors for a Supercomputer," Science, Vol. 215, January 1, 1982; and Arthur Robinson, "IBM Drops Superconducting Computer Project," Science, Vol. 222, November 4, 1983.

[121] Juri Matisoo, p. 43.

Hara and Sugano at the University of Tokyo, Professors Onodera and Otsuka at Tohoku University, Professor Iriye at Kyushu University and Professor Fujisawa at Osaka University.[122]

By the early 1970's, programs were started at Fujitsu, NTT and MITI's Electrotechnical laboratory, with smaller activities begun at NEC, Hitachi, and Mitsubishi Electric. This is somewhat reflected in patent data which shows the first appearance of patent applications in at this time. Patent activity was not, however, very significant for the subsequent five years as researchers were principally involved in educating themselves with the technology, reproducing work that had been conducted at IBM.

Then in the late-1970's, two activities began which were to act to accelerate Josephson junction research firms. The Ministry of Education had just completed a three year program with the research of Josephson junctions being one of the principal themes. The technology developed a strong advocate in the program's Chairman, Prof. Hara of the University of Tokyo, who felt that the technology was ready for industrial development. Citing IBM's plans and advances and the progress in understanding made in Japan over the previous five years through university and firm research, he argued that Josephson junctions were ripe for development as an important technology for sensing and information processing applications. Through his contacts in MITI, he began encouraging national support.

In 1979, MITI also formed a study group to identify which R&D should follow up its soon to be concluding high speed computer project. For over 15 years, MITI had sponsored a series of computer hardware and software programs in the hope of enabling Japanese industry to overtake IBM as the international leader. These efforts had, however, continually fallen short in terms of the technical success of the programs. Nonetheless, this was a high priority policy and MITI was not giving up.

From the combined influences of IBM's continuing advances in Josephson junctions, domestic progress in understanding made in the MOE program, increased firm interest in pursuing this technology, and most significantly, MITI's strong interest in IBM's interests, it was decided to begin Josephson junction work before the beginning of the next large-scale project with the support of a *Hojokin* loan. Here half of the funds for the work would be nominally provided by MITI and half by the firms. Firms which joined the program were Mitsubishi Electric, Fujitsu, NEC, and Hitachi.

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[122] These are also the six professors chosen to head the six task areas in the "Superconductive Quantum Electronics" project initiated by the Ministry of Education in 1977.

In 1980, a MITI study group advanced a plan for the next large scale computer R&D project and in 1981 the Scientific Research Computer Project was born as part of the newly created Future Technologies for Next Generation Industries program.

In previous MITI projects, Fujitsu, Hitachi, and NEC had been selected as the principal developers of the main frame computer prototypes, thus the match with these firms was easy to make. Mitsubishi Electric had in the past been assigned the task of developing peripherals, hence its experience in main frame technologies and integration was judged to be notably weaker. As a result, Mitsubishi Electric was not invited to join the program and its government support expired with the end of the *Hojokin* loan.

### - *Superconducting Electricity Generator*

The decision to proceed with the Super GM project, evolved from an earlier history of domestic prototype developments coupled with advances overseas. As in the case of the Josephson junction the target of the activity was rather clearly defined from a history of domestic prototype developments, and a history sparked and perpetuated by developments overseas. As described in an earlier section, MITI, CRIEPI, or the companies themselves had been sponsoring small prototype efforts since the mid-1970's. Thus the idea had been around and evolving for many years.

These previous MITI and CRIEPI projects had shown that the technology could be developed into a prototype on smaller scale, but it was clear that the next generation of prototype, which would be needed for relevant utility-scale testing, would be expensive. Without government support and without close utility participation firms were hesitant to move ahead.

With one exception. In 1985 Hitachi completed its 50 MVA prototype superconducting generator, a generator built on in house support. Although there were no admitted formal promises from MITI, MITI and CRIEPI both closely monitored this work as well as progress overseas. Although development in the United States had been suspended for several years, Germany was pressing ahead as was the Soviet Union. The prototype advances shown by Hitachi as well as the overseas advances convinced MITI to commit to the next step in the generator's development.

In 1985, NEDO commissioned an engineering consulting firm, Technova, to conduct a feasibility study of the development of large-scale prototypes of the superconducting generator. Technova assembled an advisory committee of individuals in high positions from the industry, universities, and government laboratories to identify the targets to be pursued, and to gather support for the project. The project was presided over by the Director of CRIEPI, Prof. Emeritus S. Yamamura, and included 12 industrial representatives, 8 professors, 8 government researchers, and 7 from the utilities.

Precisely which pieces of technical insight from the Hitachi development found their way into the ultimate program plan are unknown, but Hitachi benefited from its anticipatory development of this prototype by being awarded a 70 MVA prototype design in the Super GM project that is principally a scaled-up version of its earlier prototype.[123]

In March 1987, the advisory committee completed its report which was essentially a technical plan for the development of the next generation prototype. The recommendations of the report were formally accepted by MITI and funds were approved for the fiscal year beginning in the following month, April 1987.

Here we can see the *tatemae* of the policy-making process. For funds to be available in the fiscal year beginning in April, they must be approved by the Ministry of Finance in December of the previous year, and must have been submitted by August. This means that the decision to proceed with this project was actually incorporated into MITI plans by the spring of 1986, one year before the release of the advisory committee report. The presentation in March of 1987 was largely a formality, which had to be made before the start of fiscal year funding, and which provided a record of the process rather than a marker of the decision.

The Engineering Research Association for Superconducting Generation Equipment and Materials was formally approved by MITI on September 17, 1987.

### - *Superconducting Sensor*

The superconducting sensor project takes MITI a step further away from the technology selection process as the options were more varied and the international targets less clear.

The idea to initiate superconducting sensor research program germinated in a series of discussions held within the Electronics Industry Promotion Association. In the case of the superconducting sensor, the motivating organization was the industrial association in sensor technology. The association, with a membership of 206 organizations, acts as a clearinghouse of information and industrial statistics, a sponsor of surveys and overview studies, and a forum for informal discussions of technological needs.

In 1985, the Sensor Board of the Association began discussions with the Electronic Machinery Section of MITI about the possibility of initiating a large-scale R&D project to

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[123] Comment by engineers at Hitachi Research Laboratory.

advance sensor technology. The Board was chaired by then University of Tokyo Professor Shoji Tanaka and it had as its members, representatives, primarily at the Department Head (*Bucho*) level, from 12 of the country's major electronic and electric system manufacturers.[124] It was agreed that MITI would assist by providing funds for survey research to identify the various opportunities in sensor technology. A sensor working group was formed for this purpose and the survey activities continued for 2 years. The group reported on the range of areas of sensor applications, developed a scheme for analyzing the impact of successive generations of sensor development, and proposed four areas for R&D: 1) intelligent pattern recognition sensors, 2) a system to study the sensing functions of humans and animals, 3) IC sensors for electrical machinery, and 4) a comprehensive sensor data base.[125]

The first two of these candidates were subsequently selected as the most promising and two new working groups were formed, one for each option, to study the technical feasibility of each research project in more detail. Although the intelligent sensor option was rated as having an extremely high technical potential, it also involved a very broad range of technologies and applications - too broad to allow ready agreement on which technologies to propose for prototype development by a single research project. The magnetic measuring system for functions of the body also involved sophisticated technology but was a more clearly defined project. Thus this option was selected by the overseeing Sensor Board and recommended to MITI as the project to promote.[126]

In 1988, the high precision magnetic measuring system was proposed to the Key Technology Center for funding. The technology of the multi-channel SQUID which lay at the heart of this sensor was highly rated by the KTC evaluation panel, but there was concern over relative state of international advance and how far forward a leap the project would provide.

Thus the decision was deferred with the Key Technology Center evaluation board asking the association to more thoroughly investigate the international frontier. Because MITI was coopted into the project from the start, there was little doubt that it would get funded. However, the Key Technology Center uses an anonymous evaluation panel which

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[124] These electronic and electric system firms were Fuji Electric, Mitsubishi Electric, Hitachi Ltd., Matsushita, NEC, Oki Electric, Shimadzu, Sharp, Sumitomo Electric, Toshiba, TDK, and Yokogawa Electric.

[125] Nihon Denshi Kougyou Shinkou Kyoukai, Sensa Kaihatsu Keikaku I, Tokyo: Nihon Denshi Kougyou Shinkou Kyoukai, March 1987.

[126] Nihon Denshi Kougyou Shinkou Kyoukai, Sensa Kaihatsu Keikaku II, Tokyo: Nihon Denshi Kougyou Shinkou Kyoukai, March 1988.

is less tied to MITI's and whose function is to assure technical quality. Performance of its function put a slight impedance in the timing of the project, but the project was always safe.

With guidance from MITI, the Machine System Promotion Association provided funds for a review of the international state-of-the-art and experimentation to confirm some of the more important data on existing system performance.[127] With this additional supporting information, the proposal was resubmitted and was approved to begin sometime in fiscal year 1989. Because the KTC itself is short of funds to initiate new projects, however, only a small amount was allocated to allow the administrative functions to get organized and begin operation.

Eight companies were in the founding group, Hitachi, Yokogawa Electric, Sumitomo Electric, Shimadzu, Daikin, Seiko Electronics, Takenaka Komuten, and Nihon Shinku Gijutsu. The three principal participants are Hitachi, Yokogawa Electric, and Sumitomo Electric, which account for 66% of the capitalization contributed by the firms. Toshiba, which had participated in the intelligent sensor working group, petitioned later to be included in the project, and was granted admission beginning June of 1990.[128]

For the first year of the project, the laboratory space was being prepared in Tsukuba. In the interim, a small amount of space was rented from MITI's Electrotechnical Laboratory for computer modelling and finalizing the details of their research approach.

### - *HTS- Electron Devices*

The HTS-Electron Devices project offered an even greater technical uncertainty and again shows MITI further removed from the details of program formation. One characteristic which separated this project from the others covered there is that at the outset of the electron device project, the technologies that should be promoted were not yet defined.

While MITI was turning its attention to the formation of ISTEC during 1987, another group of scientist from ETL and the universities held informal discussions with the Electronics Section of MITI about creating a program to support the development of HTS devices. Whereas the ISTEC laboratory would be charged with fundamental research and

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[127] Nihon Denshi Kogyou Shinkou Kyoukai, Koudou Seitai Jiba Keisoku Shisutemu ni Kansuru Chousa Kenkyuu Houkokusho, Tokyo: Kikai Shisutemu Shinkou Kyoukai, March 1990.

[128] Because these are R&D investment projects rather than contract R&D projects, there is a strong desire among participating firms for equity in costs and benefits. Firms joining late are in a position to absorb all that occurred before at little cost, that is, to free ride on previous work, so late admission is rather rare among KTC programs. In this case however, little research had been initiated so the release of information was considered a minimal cost when compared against the advantage of having another major industrial organization participate in this project.

materials development, they envisioned a second activity that would explore applications. MITI realized that they would need ideas to follow the first generation of Next Generation Technology projects, and was thus eager for promising suggestions. The three themes that received the most attention were HTS Josephson junctions, HTS devices, and new devices. MITI pressed the view that to be unique the themes should be both new and use HTS materials, and the general thrust of the program was thus generally defined. A review of the international state-of-the-art showed that there were a large number of potential options, and by early summer a general program outline was included with MITI's budget proposal for the following year.

Funds had been requested from the MOF at the earliest point of the budgetary cycle, and so became available in April of 1988, along with the funds for general HTS research going to ISTEC. But the formation of ISTEC had received top priority among the MITI staff and it still was not yet clear in 1987 what kinds of HTS devices were most promising. As a result, when the funding for the project was appropriated beginning in fiscal year 1988, the plans for the project had yet to be drawn.

In the first year of project, much of the funding went to the ETL to begin general HTS device R&D. Since the technological terrain was largely unknown, MITI decided to let the firms generate the ideas. A call for proposals was issued in September of 1988, and 16 firms responded. Researchers at ETL evaluated the technical potential of the ideas and MITI staff evaluated the experience of the firms in this industry, i.e., their general commercial and technical capability, and the quality of the researchers that they were offering. Since this was research that would require creative thinking, the quality of the individuals became particularly important. In April of 1989, six projects and firms were officially announced.

All six of the firms were from among those that had been participating in the ongoing Future Electron Devices (FED) project, and all were veterans of MITI national R&D projects in computer-related technologies. The firms selected and their FED responsibilities were NEC and Toshiba which proposed stacked high density 3-D ICs, Oki Electric which proposed stacked GaAs IC technology, Sanyo Electric which proposed stacked large-capacity, multi-functional IC technology, Fujitsu which proposed a resonant tunneling hot electron transistor, and Hitachi which proposed a permeable base transistor.

- *Goto - Quantum Flux Parametron*

This project is an outlier as it falls under the jurisdiction of the STA and is sponsored by a system specifically designed to promote creative research. Given this setting, it further illustrates the distancing of the bureaucracy when frontier science is a goal.

The quantum flux parametron was an idea first conceived by Prof. Goto in 1954, using capacitors, ferrite core coils and resistors as the basic elements. Given the level of technology at that time, it was clear that it would not be competitive with the transistors being developed, and though several Japanese firms developed prototypes, the technology was generally dropped by the end of the 1950's.

Several decades passed until Dr. Goto developed a renewed interest in this idea, this time coupling the parametron with rapidly development Josephson junction technology. Between 1983 and 1985 Prof. Goto and his graduate student Kin Fock Loe developed the theory behind the device with the integration of Josephson junctions in 1984. Hitachi took an interest in Dr. Goto's work and between 1984 and 1986 contracted with Dr. Goto for the joint development of the idea. Prof. Goto noted that the Hitachi laboratory could provide very sophisticated fabrication and testing equipment which would be too expensive for his lab at Riken to purchase.

At about his time, ERATO approached Dr. Goto about leading one of their projects.

Initially, however, ERATO did not approach Prof. Goto about the parametron but about directing a project in Josephson junction technologies generally. He noted, at that time, that he had never conducted research directly in Josephson junctions and had never published in this field, so he replied that this might not be such a good idea.

ERATO, however, was not to be shaken off so easily. For ERATO, one of the most important organizing principles is that the projects are to be led by well-known scientific figures. The ERATO program has as its project leaders many of the scientific elite of the country, including individuals rumored as Japan's top candidates for the next Nobel Prize. Their reputation and leadership to some extent replaces formal technical reviews of the projects as the standards of evaluation are less clear in creative science and challenge to their leadership undesirable. The importance of industry as a leader is relatively less prominent.

In this way, ERATO hopes to attract talented young people who want to do research under these scientists, gain the confidence of the industry, which is skeptical of the unusual character of the program, and gain public visibility to support the program in general. And they wanted Prof. Goto. So ERATO asked what idea he would like to pursue under the program, and he responded, "the parametron."

When ERATO began its support of the parametron, the in-house work at Hitachi was suspended and Hitachi became one of the three centers for the research with responsibility for manufacturing prototype devices. The other centers were at ULVAC, located in Chigasaki, and Mitsui Zosen Systems Research, located in the Tsukiji area of Tokyo.

- *Formation summary*

When placed within the perspective of general theories about state behavior, these five technology and systems cases as well as the previous science cases show patterns which less reflect a "plan-rational" state than a dynamic of "reciprocal consent." But the balance of the consent shifts as the technology targets change. As the technology more clearly presses the frontier, as its complexity and uncertainty increases, the influence of the network outside of the government gains in importance. As the balance shifts to the frontier, the state is even less the generator of ideas, nor is it typically the leader in initiating the project. Neither the cases of HTS nor LTS was it true that firms lagged the initiative of MITI.[129] But the state still makes the projects happen.

The details of the projects reflect the overall priorities of the state institutions, and the state assists in forging the desired participation and, of course, in gathering resources from the Ministry of Finance. Although the size and diversity of the groups varies with the technology, an important point here for the international audience is that MITI is not seen to be instrumental in either generating the ideas or screening the options unless the options are narrow - they do not have the expertise. In some cases the push is from the industry and its associations, in some cases from the national laboratories, and in some cases professors play a role. But MITI is not an important idea generator.

As technologies become increasingly uncertain, the government's involvement will likely become increasingly distant, relying more on external networks for ideas and on the firms for specific proposals. This trend was seen in the establishment of the Key Technology Center and can also be seen in the establishment of the HTS Electron Devices Project. MITI will still look toward the collective good and the long term, but the details will increasingly be drawn from the outside.

From the perspective of more operational program formation, there are several common points in the formation of the four MITI-related projects which point to a very thorough approach to planning. First, there is typically a review of the international state of

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[129] This is contrary to the conclusions given by some others who have studies this issue such as John Alic and Robert Miller, "Commercial technology strategies in high temperature superconductivity, the U.S.A. and Japan," International Journal of Technology Management, Vol. 4, No. 6, 1989; and Japan Technology Evaluation Center, JTEC Panel Report on High Temperature Superconductivity in Japan, Washington: NTIS, November 1989.

the art. As all of these programs are intended to catch up to or leapfrog the international state-of-the-art, a thorough understanding of where that state-of-the-art is becomes a critical issue. The process of doing the background research becomes an important educational exercise to bring the knowledge of the firms up to the international frontier.

Second, we can see that the process takes a fair amount of time, usually two years, during which the feasibility study is usually conducted and molded into the project proposal.

Thirdly, technical guidance is always provided for by an advisory committee rather than MITI. These committees are typically chaired by a well known professor, who can leverage his expertise and elevated status to help settle disputes, and is typically attended by individuals from the national laboratories and, most importantly, from the firms that will eventually be doing the R&D. Planning is through a committee of the interested technical organizations.

### Timing of the project in its innovation time path - what kind of a leap is this?

As we discussed in an earlier chapter reviewing the history of cooperative programs, the targeting of prototype devices and systems was part of a clear strategy to catch up with the west. In the case of technology development, it is now commonly argued in both Japan and the United States that these programs can be cooperative because they target "precompetitive" stages of the development of technologies which themselves are substantially more advanced than research currently underway in the firms. The research, it is argued, is thus not appropriate and would serve technology base needs of all firms. Is this true? If not, what type of innovation is being targeted? Are they still in the catch-up mode? Are they attempting to leap frog? Are they legitimate contributors to public technology and to science generally?

The key variable influencing observations on this issue is the state of the technology relative to the international standard at the outset of the project. When the industry in Japan clearly lagged the west, the target was primarily catch-up. The closer the industrial level to the west, the greater the increment of advance until we see a case in which Japanese industry is enhancing its pioneering position, not just catching-up. The argument that the projects target precompetitive technologies is, however, often not correct.

In examining the five cases we find that three are directed are various degrees of leapfrogging, one at new devices, and one at a new device concept. None of these projects is a precompetitive, generic technology base activity which supports the industry as a whole.

- *Josephson Junction*

The earliest of these programs is the Josephson junction project and its goal was clearly one of catch-up. Until this Josephson junction project was initiated by MITI, there was only a very low level of research, reflected in a low level of patent applications before 1980, as shown in Figure 46.

At the time, IBM was focusing its efforts on lead-alloy or tin-alloy based junctions and this also became the focus of the initial work in Japan. These materials were being used because they were relatively easy to process. These materials melt at temperatures

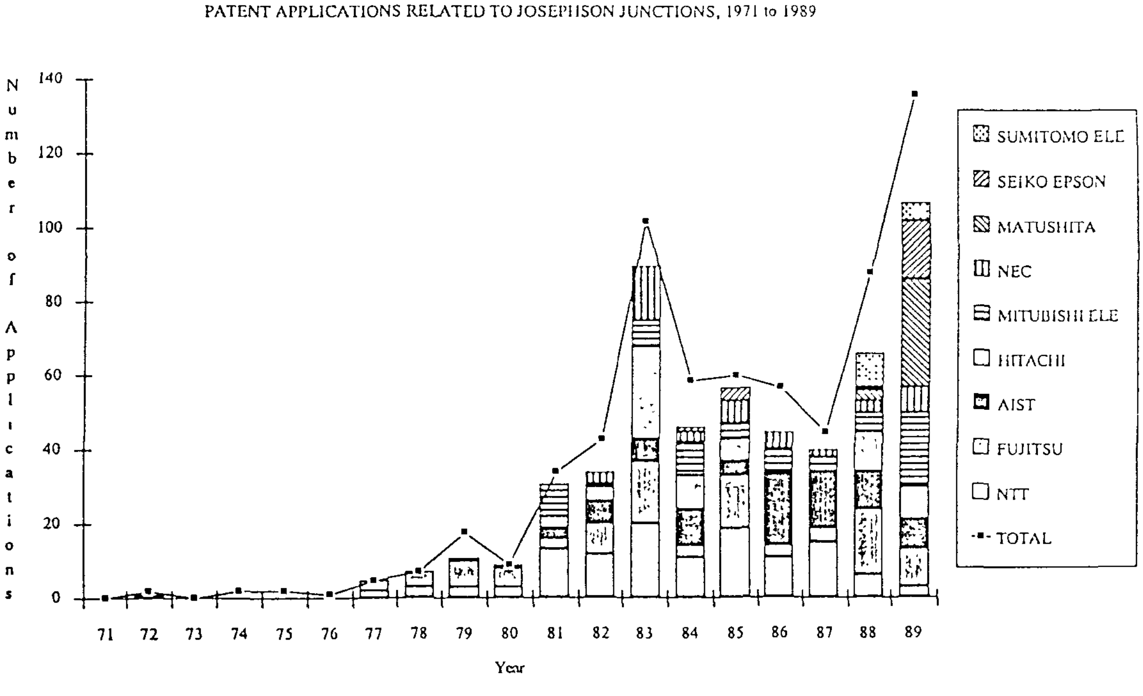

Figure 46 Patent Applications Related to Josephson Junctions (Year Announced - One and a half years after application)

below 350 C and are thus easy to evaporate into firms. However, these materials were not durable and the stress of being cycled between near zero and room temperatures caused the junctions to warp, crinkle, or in some other way fall apart.[130]

IBM scientists discovered that the performance of these junctions could be improved by using alloys of lead containing indium and gold, and by using an even more durable superconductor as the bottom electrode, niobium. Niobium was, however, difficult to form into high quality firms as its melting point is very high, 2400 C, and as it quickly absorbs oxygen, forming oxides which inhibit superconductivity. A one percent increase in oxygen leads to a one degree reduction in the superconducting transition temperature. It was in this period of learning to more effectively process Niobium that IBM discontinued its program.

Although the qualitative goals was simply to catch-up with and perhaps surpass IBM in this technology, nominal performance goals were also set. These are summarized in Table 15.

Although these goals were beyond the state-of-the-art at the outset of the project, they were not significantly so. For example, although it was known that ideally Josephson junctions could provide switching near the 1 ps level, it would require submicron technology not available at the time. Performance at 10 ps/gate did not require such technology. At the time, IBM had announced that it had achieved switching times of 6 picoseconds, with switching delays for the JJ interferometers in the 10 to 15 picosecond range.[131] This was about 10 times the speed of semiconductor devices at the time. IBM was also well into its research on a 4 K cache memory although it had not yet been successfully constructed.

Both of the systems projects also offer examples of technological leapfrogging more than of technology-base, precompetitive R&D.

- *Superconducting Electricity Generator*

If the Super GM project and the intended follow-up are completed, the superconducting generator to be developed by the MITI projects would be one of the larger operating prototypes in the world to date. But its novelty and noteworthiness were primarily in its scale, development cost and successful demonstration rather than in its targeting of new technology.

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[130] Much of the this discussion on the problems IBM had with the lead and tin junctions is from Simon and Smith, pp. 118-119.

[131] Juri Matisoo, p. 45.

Table 15. Performance Targets for the Three High Speed Devices

| | JJ Device | HEMT Device | GaAs FET |
|---|---|---|---|
| Operating temperature | Liquid helium temperature | Liquid nitrogen temperature | Room temperature |
| Logic Devices | | | |
| Integration | Above 3K gates/chip | | |
| Delay time | Below 10 ps/gate | | Below 30 ps/gate |
| Memory Devices | | | |
| Integration | Above 16K bits/chip | | |
| Access time | Below 10 ns | | |

The prototype development is divided into two stages. The initial targets of the project are three 70 MVA prototype generators. One prototype is a fast-reaction generator, and the other two are slow-reaction designs. Experience gained in the development of these designs is then planned to be incorporated into a single 200 MVA fast and slow reaction generator which would be developed in stage two, after 1996.

The development of the 70 MVA and 200 MVA generators will place the Japanese developers among the international leaders in this technology. For example in rated size, they will only be exceeded by the Soviet project and a large prototype being developed in Germany by KWU-Siemens, as shown earlier in Figure 3.3. More importantly, by project completion these Japanese firms will be much closer to commercial capability in this technology than they are today.

However, in terms of the technology, the program is not targeting major advances. Let us examine the superconducting rotors as an example. In all of the prototypes, the superconducting wires planned for use are NbTi alloys rather than $NbSn_3$. NiTi has been the alloy of choice for all previous superconducting generator prototypes and has proven a reliable option in the magnetic field range anticipated. $NbSn_3$, however, is capable of operating in even higher magnetic fields, which would allow for more compact generator designs. However, NbSn3 has proven a difficult material to construct into magnets so the certainty of their successful use if much lower. Thus in the program, NbSn3 is being researched separately from the prototype development without anticipation of its near term use. As noted in the report of the advisory committee: "We have decided to use NbTi alloy as the superconductor material since it is easily feasible at the present state of the technology."[132] Appendix C shows more graphically the performance improvements targeted fro the superconductors.

A second major component challenge is in developing a reliable refrigeration system of the scale needed. The project will target the use of a liquid helium pool-cooling method with the field windings cooled by the thermosiphoning of liquid helium in free convection. This was also the design used by Hitachi in the development of their in-house 50 MVA prototype.

A third challenge is in the actual production of electricity with the prototypes. All systems developed in Japan, and all major systems developed internationally have operated using reactive power. Electricity is fed into the generator to achieve rotation. With each of the 70 MVA prototypes, the phase will be adjusted so that active power will be generated, much as it would be in commercial operation.

Overall, however, the advances required of the system are incremental. Components which need to be improved are shown in Appendix B. This incremental character of the overall advance is reflected in a statement of the advisory report which notes that the current prototypes were chosen "to be a technology that is feasible within the range of the scale of the systems presently in existence."[133]

A future advance which would be a major step forward for the system would be the use of superconducting materials not only in the rotor but also in the stator and in the power transmission components. As described earlier ,whereas the rotor is stationary and operates with a DC current, the stator spins at very high speeds and operates with an AC current. The development of superconducting materials than can operate with high fields in an AC current is still in a stage of bench scale experiments and far from ready for large scale demonstration.

Thus the technology necessary for a "fully" superconducting generator, one with both a superconducting rotor and stator, and the technologies needed for superconducting

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[132] S. Yamamura, "Feasibility Study on Superconducting Machinery and Materials Technology Related to Electrical Power Generation (Summary)," Tokyo: New Energy Development Organization, March 1987, p.5.
[133] S. Yamamura, p. 13.

transformers and transmission system are being researched as secondary tasks attached to the program. The same is true of high temperature superconducting materials. As the plans for Super GM were in reality concluded before the confirmation of the high temperature phenomena, these materials were not considered in drawing up the program. Given the high level of interest in the possibilities of this new discovery, however, both MITI and the manufacturers were looking for ways to channel money to their development. The project provided a convenient vehicle as all of the nations major cable and wire manufacturers and developers of superconducting wires were already on contract.

Superconducting AC transformers developed to date are still much smaller than would be needed for commercial operation. The largest is a 500 kVA laboratory model developed in 1987 by Toshiba with the support of the Central Research Institute of the Electric Power Industry (CRIEPI). The second largest transformer developed is a 100 kVA design developed by a manufacturer in France.

Unlike the application of DC wires to magnets, AC superconductor development has had a much shorter history. The first experiments were reported in France, and to date most of the development has centered there and in Japan. Experiments in the United States generally fizzled out in the 1970's when a lack of new generator plant orders dampened enthusiasm for work on new transmission technology.

The problem with AC wires, is that unlike superconducting DC wires, losses do occur. The sinusoidal signal creates a hysterisis loss in the wire which generates waste heat. This heat can raise the temperature of the wire above its superconducting critical temperature, causing it to lose its superconducting capability.

To minimize this loss, the diameter of the wires must be kept extremely small. Current designs use wire with submicron diameter, which compares with 10-100 micron which would be used for DC cables.

For power transmission, DC transmission is also possible, but the costs are still very high with current technology. Unlike generators which have a small surface to volume ratio, transmission cable have a large surface to volume ratio, which makes cooling much more expensive. Aiyama estimates that these cables only appear to be economically attractive at capacities of several GVA, which is far beyond the size of current systems. Even with the reduced refrigeration requirement of recently developed high temperature superconducting materials, the break even point is near 3 GVA.[134]

Given the importance of overcoming this barrier to establishing a fully superconducting system, it is a bit of a mystery that this topic does not receive greater

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[134] K. Aiyama. op.cit.

funding priority. But this can be partly understood by realizing that a principal goal of the program is not technical.

Technologically, the Super GM project may seem to lack luster because of the absence of a major targeted technical leap or intentions to overcome major technical obstacles. However it is likely that it was the absence of major targeted advances that enabled the activity.

This is not a technology base activity but one directed at demonstrating a prototype of a new technology to a conservative industry - the electric utilities. Electricity generators for large power plants are extremely capital intensive investments, with costs on the order of hundreds of millions of dollars.

Because of these high costs, it is important that the generators run as close to full capacity as possible. Any failures in the generating system would result in a direct loss of power revenue, increased costs because of the need to activate less efficient supplemental power equipment, and customer complaints stemming from any disruptions that might occur. The industry boasts that in 10 years, with 6,000 generators operating, there have only been four generator accidents that have caused the unanticipated shut-down of a generating system.

Thus electric power firms heavily weigh the down side risks against any performance increases, and in this case some argued that the increases were only incremental. The main goal of the Super GM project is to assuage these concerns by displaying the reliability of a system operating near commercial conditions. A primary goal is co-optation of the user.

### - *Superconducting Sensor*

The Superconducting Sensor project is aimed at leapfrogging the current level of technology in the western countries. Currently, 7 channels is the largest number employed by a single sensor system on a commercial magnetoenphalograph. This is a machine developed by Biomagnetic Technologies Inc., BTi, (Model 607) which has been available on the market since 1984. In June of 1989, Seimens announced the development of a 31 channel SQUID system (KRENICON), and in August, BTi announced the development of a 37 channel prototype. In Japan, however, manufacturers are still only offering single channel devices and at the start of this project, the proposing committee asserted that no firm had started significant development of a multichannel system.[135]

The Superconducting Sensor project is targeted to leapfrog these overseas developments by developing a prototype 200 channel device. Whereas current devices are very time consuming to use, sometimes requiring hours for a full scan, during which time metabolic conditions can change, the 200 channel device is expected to provide real time imaging of the operation of the brain. Through an operating version of this system it is hoped that researchers will be able to follow the complex paths of electromagnetic signals within the brain and brain stem, with the ultimate desire of understanding how the brain processes information.

In addition, program promoters note that ultimately this type of ultrasensitive imaging technology can be extended to a range of other applications that include materials research, the analysis of high speed electronic processes such as those that occur in supercomputers, and the search for natural resources. Further, knowledge gained about the way the mind processes information is expected to have a significant impact on information network designs and computer architectures. The spin-off effect, in other words, is argued to be broad.

While this leapfrog may allow a fundamental breakthrough in science through its eventual application, the system itself primarily involves a set of more incremental technical challenges and a challenge in integrating all of the improvements that need to be made - a challenge to systems development and integration.[136]

Principal technical challenges that have been identified by the program planners are summarized on Table 16.

Some of the principal challenges among these have been summarized by program director Mitsuo Ai as the following:[137]

1) System technology - Integrating all of the needed component developments so that the signals received can be translated into useful information. This would include the ability to probe for sources of electromagnetic signal in a given field and the development of image management algorithms. This would also involve the development of a system

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[135] Nihon Denshi Kogyou Shinkou Kyoukai, Koudou Seitai Jiba Keisoku Shisutemu ni Kansuru Chousa Kenkyuu Houkokusho.

[136] This point is emphasized heavily in the proposal of the evaluating committee. See for example the above Nihon Denshi Kygyou Shinkou Kyoukai report.

[137] Mitsuo Ai, "Chodendo Sensa Kenkyujo to Kenkyu Gaiyo," Denshi Kogyo Geppo, Vol. 32, No. 6, 1990, pp. 12-16.

Table 16. Magnetoencephalograph System Elemental Technologies[138]

| Technological Elements | Research Topics |
|---|---|
| HARDWARE | |
| SQUID flux measurement | Multi-Channel; High integration; High reliability |
| Input coil | High ability to suppress noise; film |
| Noise suppression equipment | Low temperature construction |
| Cryostat | Reduced consumption of helium; Adapted for the human body |
| Helium refrigeration | Compact; high reliability; high efficiency; low noise |
| Magnetic shield | Increased shield effectiveness; High temperature superconductor construction |
| SOFTWARE | |
| Electronic model of of the brain | Higher precision |
| Magnetic source analysis algorithm | Multiple magnetic sources; highly efficient algorithms |
| Image management algorithm | Three-dimensional image |
| Image display algorithm | Three-dimensional movement display |

that could automatically calibrate the SQUIDs, automatically adjust the circuits for the particular computation, and sense phantom images.

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[138] Nihon Denshi Kogyou Shinkou Kyoukai, Koudou Seitai Jiba Keisoku Shisutemu ni Kansuru Chousa Kenkyuu Houkokusho, p.5.

2) SQUID technology - Improving the reliability and sensitivity of the SQUID element and the uniformity, as well as the ability to test for these characteristics.

3) Shielding and Refrigeration technology - Reducing the level of magnetic noise from 1/1,000 common in today's machines to 1/100,000, preferably with the use of a shield which employs high temperature superconducting materials. Here, magnetometers are being investigated to replace the gradiometers used currently. Although there are a number of laboratories in Japan working on this technology, research must still overcome problems such as that arising because the vibrations of trapped flux within the material creates a level of noise of the same order of magnitude as that trying to be achieved by the shield.

In addition, there is a need to develop a small, high efficiency, low noise method of supplying liquid helium refrigeration to the elements.

As one can gather from the table and the priorities, the project will require incremental advances on a number of technological fronts, and the integration of these advances into a system. However the system but is not revolutionary in any of its component developments.

### - *HTS Electron Devices*

The HTS Electron Devices Project can also be viewed as a state-of-the-art activity that will give the developers a substantial lead in the technology. None of these concepts is entirely new as each was being explored with traditional LTS materials before 1987. The charge injection proximity effect device being developed by Toshiba was initially developed at IBM, the single electron tunneling device at NEC was developed at Bell Laboratories, and the low-energy injection-type superconductor base device at Sanyo was initially developed by IBM and at Fujitsu.

Even as LTS devices, however, these concepts were at the state-of-the-art of electronics research, so the novelty of applying HTS materials was in seeing whether oxide materials could also be manipulated to provide the same phenomena. The targets are legitimate leapfrog beyond existing technologies and reflects the leading international position of the industry in Japan.

### - *Goto - Quantum Flux Parametron*

The QFP is a leap beyond the Josephson junction in both its performance characteristics and the physical phenomena upon which it relies. As described earlier, both the switching speeds and heat loss characteristics of the QFP could significantly outperform both existing technology and the Josephson junction. In addition, the use of magnetic flux quanta as the switching medium is a major departure from current practice.

As there was very little work in this technology occurring elsewhere in the world, the work of this project is pioneering. Although not revolutionary in its contribution to a generic, technology base, or to a fundamentally new theory of a physical phenomena, the QFP is a novel idea which at a minimum warrants being labelled a significant technological leap.

#### - *Technical Target Summary*

From the above discussion of the R&D goals we could see that the cases of the Josephson junction and the superconducting generator reflect only incremental advances in technology performance, with the superconducting sensor and HTS-SC cases targeting a greater leapfrog. In none of these cases, including the parametron, do we see research opportunities that are truly "technology base" and "precompetitive."

### Organization of the project

How do firms cooperate? Do firms cooperate?

In this section our five programs will be analyzed to provide some insight into these questions. If it is collaborative R&D that policy is trying to mimic in the United States, then we should first be confident, that collaboration is indeed occurring and second, have some understanding of the circumstances under which collaboration is most productive.

To conduct this analysis we will rely upon four types of information: the organization of the projects, patent applications, publications, and information provided in interviews. By examining the organization of the programs, we can address questions such as the following. Is the program organized to encourage or to rely upon cooperation? Are the researchers from different firms grouped together to conduct research? Are their research tasks interdependent? Are there enticements for cooperation or organizational procedures which promote collaboration or communication?

In addition to the organizational structure, we can also look at indicators such as joint patent applications and coauthorships to see if there is confirming evidence of collaboration in the output of the programs.

In all of these cases, affirmative evidence of collaboration among competitors was generally lacking. There is only limited evidence of programs organized in ways that would involve the mixing of personnel from different firms. Where cooperation does seem to exist, it is planned between participants with complementary interests, in vertical or diagonal linkages. Even in these cases however, the work on both sides of this linkage is largely autonomous. Between firms in the same sector, we find strong tendencies toward insulation between firms and a structure which emphasizes competition rather than cooperation. Cooperation between competitors, we will see, is very difficult.

I will begin with the three device cases and then proceed to the systems cases.

### - *Josephson Junction*

The High Speed Computing System project follows the organizational structure of all of the projects under MITI's Future Technologies for Next Generation Industries program. The firms are nominally collected into a research association created for the project, the Scientific Computer Research Association. As in the case of all of these associations the Director , Mr. Miyazawa, has come from MITI through an *amakudari*. The office is responsible for the administrative functions of the project and is staffed with personnel dispatched from each of the companies.

With the participants administratively housed under one roof, does this mean the firms are collaborating in their R&D? The official position of the Association is that they are, and the association prefers not to discuss the division of responsibilities and labor. In their annual technical reports, for example, the work of the firms is lumped together in a synthesized description of progress in Josephson junctions. "We encourage cooperation," is the formal response.

As all of the participants were clearly lagging the international standard, there were efficiencies to be gained in collecting and sharing public information to improve this status. Interviews with researchers in each of the laboratories indicates that there was some exchange of technical information about their device development early in the program, but the exchange became more formalized and less open as the program advanced. Each firm was capable, ultimately, of developing and marketing the device on its own, and each company would be a competitor in the market place. Thus the ultimate organization needed to consider these somewhat conflicting incentives to share and compete.

So despite the official response, this project seems to be a classic example of a "cooperative" program in which there was far more insulation between the firms than cooperation. The three manufacturers, Hitachi, Fujitsu, and NEC were each given separate tasks. NEC was primarily responsible for developing the memory device and Hitachi and Fujitsu were assigned logic devices. Each worked in its own laboratory with its own staff.

Examination of publication and patent data supports this conclusion. Accessing the JOIS data base of publications for articles on Josephson junction research published by each of these firms in Japanese, we can see a steady increase from 1985 to 1989 in Figure 47. None of these publications, however, were written jointly between any of these three firms, or between these firms and other firms. The only cases of cooperative publication were between a firm and its affiliate, Fujitsu and Fujitsu Communications (2 cases), and between a firm and a program in which it is participating, Hitachi and the Goto Parametron Project (1 case).

Patent application data reveals a similar pattern of research insulation. Figure 48. shows the dates of patent applications by the three firms, AIST and Mitsubishi Electric. We see a significant increase in applications two years after the start of the MITI program among all participants. There are, however, no cases of joint applications between the three firms, and only one case between one of the firms, Hitachi, and the Electrotechnical laboratory.

Until 1986, all of the patents developed by project funds were nominally 100% owned by the government. As a result, all of the patents were assigned to AIST so it is difficult on the surface to know whether the pre-1986 patents were developed cooperatively between firms. An examination of these patent applications and their authorship, however, reveals that all can be attributed to researchers at MITI's Electrotechnical laboratory, not to the firms. Patent applications since 1986 would show joint institutional ownership if this occurred, and the data do not provide evidence of a single case.

The figure shows, however, that the firms, on their own, became quite active in submitting applications independently of the program. Why this heavy patent activity outside of but not within the program? The reason seems to stem from an operational "gentlemen's agreement" which allows the firms to evade the government ownership issue by formally submitting patents independently, even if one could, on close inspection, make a case that the patent came out of the government project. This would preserve the incentive to develop and apply for patents among the firms that would disappear if they had to give ownership entirely to the government.

Thus where there is little need to cooperate, firms will not do so just because they are in a "cooperative' R&D program. Each of the firms had the equipment that it needed and enough in-house expertise. The incentives to cooperate as they gained greater in-house capability were few.

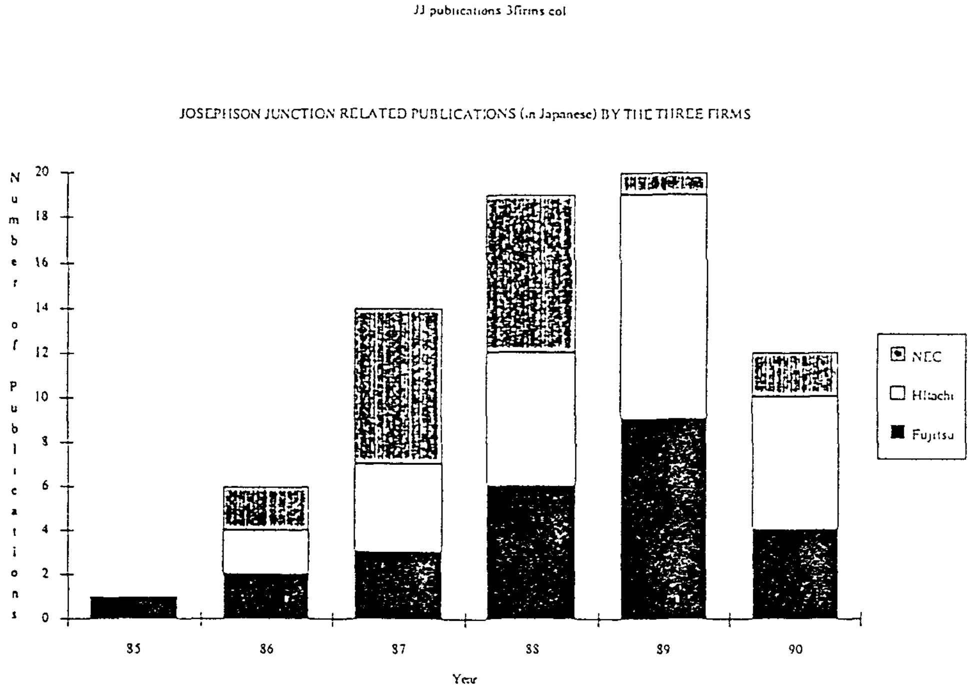

Figure 47 Journal Articles Related to Josephson Junctions

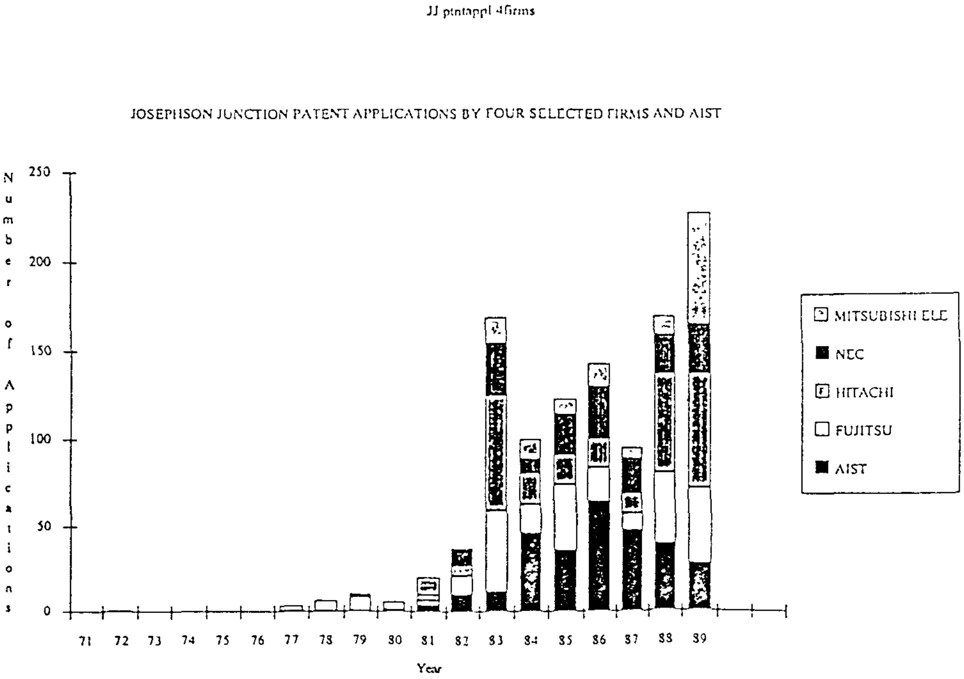

Figure 48 Patent Applications Related to Josephson Junctions by MITI Program Participants

Finally, in addition to these firms there was the government laboratory. ETL had the longest history in this technology in Japan. Was it a significant nurturing force for the firms? Although ETL provided the testing and evaluation expertise for the program, in the way of research, ETL also followed its own path. Researchers at ETL were free to address all elements of a Josephson junction computer and did so. The results of these separate research activities are reported separately from the work of the firms in the program's final technical report,[139] with the synthesis of these developments coming together in ETL's development of a four chip "Josephson computer" in 1989. This was developed independently from the activities of the firms.

The one important contribution that ETL did make to the activities of the firms was its testing of new materials for the Josephson junction, Niobium based alloys rather than lead, which some feel was the most important technical advance in the project. This will be described in more detail when discussing the outcome of the program.

Outside of the program, patent applications reveal little additional evidence of free cooperation between competing firms. Instead the applications fit one of two patterns. Either the joint application was submitted by a *keiretsu* affiliated firm, or it was submitted jointly with an individual outside of the firm, typically a university professor, or with a government laboratory. Hitachi, Ltd., which had the greatest number and variety of joint applications, cooperated with either government research organizations, 12 cases, or with one of its affiliates: Hitachi Engineering (3 cases), Hitachi Microelectronics (3 cases), and Hitachi Cable (1 case). The other firms with joint applications, which totaled 11, cooperated with individuals, 10 of the 11, or a government laboratory, one case. The most active here was Nippon Kokan which had 27 patent applications with Tokai University and Prof. Tachikawa. Sharp and Toshiba followed in rank with two joint applications each.

### - *Goto - Quantum Flux Parametron*

Following a structure very typical of projects in the ERATO program, the QFP project is organized around three primary research themes, with research in three different locations. The three themes are fundamental properties, magnetic shielding, and computer architecture. The first theme is being researched in space rented from the Hitachi Central Research Laboratory in Kunitachi, on the outskirts of western Tokyo. Some of their principal tasks are developing the QFP as a logical and memory element and as a magnetic

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[139] Denshi Gijutsu Sogo Kenkyujo, Ogata Kogyo Gijutsu Kenkyu Kaihatsu, Kagaku Gijutsuyo Kosoku Keisan Shisutemu no Kenkyu Kaihatsu, Keika Happyokai Ronbunshu I, Tsukuba: Denshi Gijutsu Sogo Kenkyujo, June 1990.

flux sensor, and designing the QFP for three-dimensional integration as a computer element. The second theme is being pursued in space at the laboratory of ULVAC, Japan in Chigasaki, with the group focussing on the removal of trapped fluxoids in the magnetic shields and the development of an efficient and reliable helium liquifier. The third group was initially located at Mitsui Zosen Systems Research in Tokyo, with their research targeting new computer architecture based on the QFP and writing the software.

The QFP project would at first seem like a different form of project which would be more amenable to cooperation. Recall that the formal goal of the ERATO program is to raise creative minds by allowing them to conduct research in advanced fields of science. Formally researchers that participate must leave their positions in their home institutions and then have their salaries paid for by ERATO. The independence of the individual is further emphasized in intellectual property policy with half of the ownership of patents going to the individual, not their home firm, and half to ERATO's parent organization, the Research and Development Corporation of Japan (JRDC). Furthermore, in a nominal attempt to prevent a single firm from dominating the program, a maximum of two researchers are permitted to participate in the program from the same organization. And finally, in an attempt to reduce the influence of internal peer pressure, the research must be conducted in at least three different locations, with a preference early in the program that these locations be geographically distributed rather than concentrated. With this emphasis on the individual and safeguards against company pressure, one might expect that if not true collaboration, at least a free mixing of researchers would be observed, with their pursuit of creative science being the primary influence on behavior.

In spite of all of these administrative safeguards and the near-basic state of the research in this area, we find that the competitive interests of the firms again become very influential in the actual operation of the program.

From Hitachi's perspective, it would like to explore the feasibility of the practical use of this device for eventual commercial application. From ERATO's perspective, although the advance of the creative science is the principal stated goal, they would like to show that their research is also of practical significance, which means that they would like firms to take an interest in further developing the technology. And for Prof. Goto's perspective, he would like to both see the development of his idea be a success and see its eventual application. Thus there were incentives among all three parties to give priority to the practical development of this technology, with the nominal goals of fostering independent and creative minds taking a lower position in actual priority.

Midway through the program, the three facilities were consolidated into effectively two sites, with the computer architecture task at Mitsui Zosen Systems Research moving to

Hitachi's Central Research Laboratory. It was still a separate laboratory, but much closer in proximity. Prof. Goto echoed a comment also made by other ERATO leaders, which was that it is much more practical for the advance and management of the program to have the facility closely located rather than dispersed as the ERATO office initially desired.

Secondly, among the five research staff drawn from the firms, all remained with the laboratory associated with their home institutions. The firms are naturally more interested in keeping their own staff at their research facility which is perhaps one reason why this program, like many ERATO programs, has to reach out to fresh university graduates and foreign researchers to complete the research team. Five of the researchers are from universities in Japan as fresh graduates or from research posts, and five were from overseas institutions, primarily academic.

Thirdly, although the limit of two dispatched researchers is enforced in this program and generally obeyed in ERATO, there are ways of adding a presence if desired. The group leader is not counted as research staff and this leader is typically assigned by the hosting laboratory. So the Hitachi site group leader was from Hitachi, the ULVAC group leader was from ULVAC and the Mitsui site group leader was from Mitsui. In addition, the job of technical advisor is also not a research staff position, and this individual has also been dispatched from Hitachi. And finally, although not apparent in this project, a firm can dispatch researchers to ERATO at its own expense, and these researchers are not counted as ERATO staff.

The net effect is that these practical incentives and responses in organization come to determine actual operation. The tasks are coordinated between the three research themes, but there seems little reliance on inter-core cooperation. The firms participate for the perceived value of the technology and organize to try to exploit that technology, with the more formal goals of encouraging creativity and enlightenment tertiary in their priorities. Although different in form, ERATO becomes a vehicle for the development of an advanced idea with commercial promise, and the opportunity to appropriate that promise, has a strong influence on the participation of firms and the operation of the project.

### - *HTS - Electron Devices*

Perhaps an even greater test of the precompetitive cooperation argument is the organization of the HTS Electron Devices project. Here the formal organization is again collective and the distance from the market of the technologies being developed probably quite far.

Administration of the project was placed in the existing Research and Development Association for Future Electron Devices which was established in 1981 to administer two projects in MITI's new Basic Technologies for Next Generation Industries Program. Two committees were formed to guide the project, one a steering committee, the Overall Investigation and Survey Committee, consisting of 2 ETL researchers, 4 professors, and researchers from the 6 companies. A second was the Technology Prediction Committee for Superconducting Devices, composed of an ETL researcher, 4 professors, and 10 company researchers. The purpose of this latter committee was to assure that the project incorporates information about new developments in HTS devices abroad.

The research tasks, however, were largely insulated. As each of the devices is discreet, each can be entirely developed and appropriated within the scale of a single firms. As a result, even though these technologies are far from commercialization, they are not being developed collaboratively. The firms and their assigned responsibilities are shown in Table 17.

For the researchers in the firms, the funds again provide for the purchase of additional research equipment and provide legitimacy to pursue this general theme within the firm. Although the firms are assigned one theme from the project, each firm is on its own pursuing parallel and related themes with entirely in-house support. The government project is thus leveraged for the support of a broader range of research, and this research more generally leads the firms to act as competitors rather than cooperators.

Since the actual promise of these devices was generally unclear, the program was designed to accommodate changes at the end of each of the two interim evaluation periods. Goals could be redefined, technologies could be changed, and firms could be dropped or added. After the first general review of the in late-1990, the six firms kept the same thematic thrusts, but two additional firms which proposed intriguing ideas were added. Sumitomo Electric joined the program to pursue a superconducting channel-type 3-terminal device, and Mitsubishi Electric joined to develop a micro-vacuum tube with a superconducting emitter. As in the original six firms, these two firms had also been participating in the first generation electron device projects. Sumitomo Electric had been working on a superlattice MODFET, and Mitsubishi on an image signal processor using stacked large-capacity, multi-functional IC technology.

Table 17. Technical responsibilities of firms participating in the HTS-ED project

| | |
|---|---|
| Ultra-High Speed Device Technologies | |
| Proximity Effect Devices | |
| a) Field effect design | Hitachi, Ltd. |
| b) Charge injection design | Toshiba |
| Superconductor Base Devices | |
| c) Low-energy injection design | Sanyo |
| d) High-energy injection design | Oki Electric |
| New-Functional Device Technology | |
| Single Electron Tunneling | NEC |
| Localized State Tunneling | Fujitsu |

Systems Projects

The cases of the systems projects would seem to present additional opportunities for cooperation because of the variety of skills needed for development. But is this what we observe?

In both the cases of the Super GM project and the superconducting sensor project, the organization of the activity shows a clear complementarity of interests that arises from the variety of skills needed to develop system prototypes. The organization also shows that firms in the same sector are not expected to cooperate, and that the tendency to appropriate still strongly influences the shape of the organization.

- *Superconducting Electricity Generator*

All of the firms participating in the Super GM project are administered by the Engineering Research Association for Superconductive Generation Equipment and Materials. The Director, Mr. Ageta, is once again an *amakuradi* from MITI and the staff for the association is provided by the participating firms.

The overall organization of the Super GM project reflects the main component development tasks of the system. The participants can be categorized into four main development groups: superconducting cable and wire suppliers, refrigeration developers, overall generator system developers, and systems users.

However, within each of the groups shown, there are several firms. There are six firms supplying the superconducting cables and wires, two firms responsible for the refrigeration system, three firms charged with developing the generator, and three utility organizations. So two questions arise regarding cooperation. Do these firms cooperate well within the groups? Do these firms cooperate freely between the groups?

An examination of the research organization within each of these groups reveals about the same level of cooperation between competitors that we found in the Josephson junction case: little. The organization shows that the tasks of the firms in the same group are all discreet, and that the organizational design does not rely on any cooperation occurring. Competitors are not expected to cooperate.

Table 18 shows the technological assignments for each firm. Each of the three generator manufacturers were assigned responsibility for three different 70 MVA prototypes. Hitachi was assigned the slow excitation response design which would employ a high stability superconductor design. Toshiba was given a different slow excitation response generator which employed a high stability design, and Mitsubishi was given responsibility for developing a quick excitation response machine with a high current density. Maekawa is given responsibility for producing the refrigeration equipment for the 70 MVA unit and divides responsibility with IHI for different aspects of the eventual 200 MVA refrigeration system.

Where it might seem that cooperation might occur because of organizational placement is between the various cable manufacturers. Furukawa Electric, Sumitomo Electric and Hitachi Cable are all assigned to the slow response machines and both Furukawa Electric and Sumitomo Electric are assigned to the fast response machine. But investigation of their activities reveals that there is minimal cooperation occurring between these firms.

As in the case of the generator and refrigeration manufacturers, research in the cable and wire firms is done at the home laboratory and there is no exchange of researchers between firms. Communication occurs through more formal technical gatherings, which occur at some level on a bimonthly basis, and none of the tasks defined for any of the members relies on cooperation between firms in the same box. According to sources involved in the project, the competition between the cable and wire firms is the greatest

Table 18 Technical Assignments of Participants in Super GM

| Equipment | Firm |
|---|---|
| Generators | |
| 70 MVA slow response, high stability | Hitachi, Ltd. |
| 70 MVA slow response, high current | Mitsubishi Electric |
| 70 MVA fast response, low loss | Toshiba |
| Refrigeration | |
| High reliability system for 70 MVA prototype | Maekawa |
| Refrigeration for the 200 MVA system, Oil-free screw | Maekawa |
| Refrigeration for the 200 MVA system, Oil-turbine | IHI |
| NbTi wire | |
| Slow response generators | Furukawa, Sumitomo, Hitachi Cable |
| Fast response generator | Furukawa, Sumitomo |
| Manufacturing methods | Furukawa, Sumitomo, Hitachi Cable |
| $NbSn_3$ wire | |
| Slow response model | Furukawa, Fujikura |
| Manufacturing methods | Furukawa, Sumitomo,Fujikura, Hitachi Cable, Showa, Kobe Stl |

because the material that they are providing to the project is cases commercially available, and thus relevant to their market activities. Major advances in NbTi cable are not required for the prototypes, and $NbSn_3$ development, which will not be used in the prototypes, is development that these firms were conducting prior to the start of the project. Because these materials touch directly upon their commercial interests, there is little desire to cooperate and the program anticipates little.

To achieve some of the economies of scale while at the same time accommodating these competitive incentives, a testing center has been established for conducting some of the high field experiments. Using space in CRIEPI's research laboratory in the Komae area of Tokyo, the facility will have a large testing apparatus which can generate a 7 telsa magnetic field and 10 tons of mechanical pressure. This device is intended to test the stability of the superconducting wires that will be used in the rotor under abnormal, transient environments which might occur in the event of a system error.

What about cooperation between the boxes? Does this appear to be something which happens freely? While there is of course some level of cooperation, the relationships between the cable and wire firms and the generator prototype developers in the project shows a coordination of complementary interests but competition between the principal developers.

Recall from our earlier discussion that many of the cable and wire firms in Japan were engaged in long-term and often exclusive arrangements with systems manufacturers. The most exclusive arrangements were between Hitachi Cable and Hitachi, and Showa Cable and Toshiba. Furukawa Electric and Sumitomo Electric are the largest integrated manufacturers, with the ability to go from raw material to magnetic product are are generally less bound by these supplier-developer ties.

Table 19 summarizes the linkages between the materials suppliers and systems developers. Most notably, Hitachi Cable is seen to solely supply Hitachi, Ltd. and not the other prototype developers. The two integrated cable manufacturers, Furukawa Electric and Sumitomo Electric find themselves in the advantageous position of not being limited by exclusive relationships and can serve all three developers. Showa Cable is generally kept to the side, along with the more minor cable developers, Kobe Steel and Fujikura Cable. These firms are given the task of developing the more advanced NbSn3 type of superconducting wire material which is not planned for use during the current project. These firms are thus not teamed with one of the systems makers.

Thus the two more integrated firms without *keiretsu* relationships are cooperating with all of the manufacturers, whereas the firm with the primary *keiretsu* relationship sticks with its partner. Among these matched firms then, where the *keiretsu* existed, it persisted.

In sum, cooperation between competitors is not designed into the organization.

- *Superconducting Sensor*

Table 19 Relationships Between Materials Suppliers and Systems Users

| | Furukawa Electric | Sumitomo Electric | Hitachi Cable | Fujikura | Showa Cable | Kobe Steel |
|---|---|---|---|---|---|---|
| Hitachi, Ltd. | √ | √ | √ | | | |
| Toshiba | √ | √ | | | | |
| Mitsubishi Electric | √ | √ | | | | |
| Primcipally ($NbSn_3$ wire) | | | | √ | √ | √ |

In the case of the superconducting sensor project, however, we might expect that an example of cooperation among competitors can finally be found. The rules of the Key Technology Center require that these consortia establish themselves at joint centers, with the consortia having ownership over any patents and know-how developed. Thus there is a central facility in Tsukuba with individuals dispatched from their home institutions for two to three year rotations. Like ERATO, the Key Technology Center desires an arms-distance policy with the home institutions.

Like most R&D oriented KTC investment projects, evaluations are conducted at both strategic and research planning levels. At the strategic level, a steering committee will be gathered twice a year to discuss the general direction and thrust of the center. These committee members include university professors, senior researchers from the government laboratory (ETL), and upper level management from the participating companies. At the research level, department and section heads from the participating firms will gather together with ETL researchers about four times a year to review research progress and to make incremental changes in research strategy.

Thus on the surface, this seems like a plausible arrangement because the technology is a substantial advance beyond the current state-of-the-art, and a substantial leap beyond the current research activities admitted to by the participating firms. The formal argument posed by participants is that development of this type of multichannel device is too great a risk for any single firm.[140]

Whether or not this is true, the firms still seem to gain in a number of areas. One such area could be the development of the control and analysis algorithms. Software

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[140] Nihon Denshi Kogyo Shinko Kyokai, Kodo Seitai Jiba Keisoku Shisutemu ni Kansuru Chousa Kenkyu Hokokusho, p.5.

development is a skill at which Japanese are still relatively weak at relative to their overseas competitors, so the pooling of resources to address this weakness and the common training provided can be seen as a collective, transferable outcome of the activity. A second area would be the systems integration knowledge gained through the development process. As advances need to be made on a number of technical fronts, and these advances combined, firms experienced in both are likely to have an advantage in the eventual development of commercial devices. Being out of the project means being handicapped should such knowledge be effectively developed.

At first glance it thus seems as though the administrative requirements of the program and the potential collective gains of the technology would provide for that elusive cooperation among competitors on advanced prototype technologies.

Actual practice, however, shows an organizational form which must still be responsive to the competitive interests of the main participants.

The participants in this research corporation bring expertise in three areas: SQUID based technologies and sensors, refrigeration, medical diagnostic software, and magnetic shielding. Table 20 lists the firms and the principal relevant skill which they bring to the

Table 20 Participating Firms and Their Expertise

| | |
|---|---|
| Hitachi | Josephson junctions, Medical equipment, Parallel processing software |
| Yokogawa Electric | SQUIDs, Medical equipment |
| Sumitomo Electric | SQUIDs, Medical equipment, Magnetic shielding |
| Seiko Epson | SQUIDs, Precision sensors |
| ULVAC | SQUIDs |
| Toshiba | Medical equipment |
| Daikin | Refrigeration equipment |
| Takenaka Construction | Conventional magnetic shielding |

Figure 49 Relationship Between Firms in the Project

| Supporting equipment | → → → → | Systems | ← ← ← ← ← | Sensors |
|---|---|---|---|---|
| Daikin | → | Hitachi | ← | |
| (Refrigeration) | → | | ← | |
| | → | Yokogawa Electric | ← | Sumitomo Electric |
| | → | | ← | |
| | → | Shimadzu Mfg | ← | Seiko Epson |
| Takenaka Construction | → | | ← | |
| (Magnetic shielding) | → | Toshiba | ← | ULVAC |
| | → | | ← | |
| | → | | ← | |
| | → | | ← | |

program, and Figure 49 shows the relationships between their principal technical responsibilities for the project.

Hitachi has done rather extensive research on Josephson junctions for computers and is the only such firm in the consortia. Yokogawa Electric and Sumitomo Electric have been conducting research on SQUID devices, as to a lesser extent have Seiko Epson and ULVAC. Sumitomo Electric is also the primary supplier of high temperature superconducting materials for this project. Daikin is a major manufacturer of refrigeration equipment, including liquid helium refrigeration, and Takanaka Construction brings skills in magnetic shielding. For Takanaka, advances in HTS are thought to hold significant promise for magnetic shielding construction in large buildings.

To encourage some sense of equal treatment and cooperation, the consortia will be rotating its directorship among the three main investors, and will select a research leader from a national laboratory rather than one of the firms. Administrative leadership of the consortia is scheduled to rotate every two years with Hitachi sending the first administrative head, Dr. Mitsuo Ai, Yokogawa Electric following with the next two year posting, and Sumitomo Electric assigning the final head. These three firms account for 75% of the total firm investment. To direct the research, the members sought an individual from a more neutral organization, which lead to the recruitment of Dr. Kato, a researcher from the Electrotechnical Laboratory.

In the beginning year of the project, it is anticipated that 20 researchers will be activated to conduct simulations, paper analyses, and to help prepare the laboratory. Once fully operating, this number is expected to grow to 30.

What is also clear, however, is that these SSL firms bring competitive interests to the endeavor. Hitachi and Yokogawa Electric, two of the three program leaders, Shimadzu Manufacturing, and the new addition to the project, Toshiba, are Japan's leading manufacturers of sophisticated medical equipment. These firms are, for example, Japan's top four firms in sales of MRI devices.

Thus in program operation, cooperation is only partially achieved, with the competitive interests of the firms playing an influential role in the execution of the research. Although there is a central research facility, much of the hardware research will conducted by the participants in their home laboratories. At the time of this writing the software development at the central facility is underway, but there is still negotiation over how the hardware research will be coordinated. While the software writing is more suited to being a collective activity because of the critical mass needed for timely development, the hardware components can be largely developed by the firms in their own laboratories, and this is what they would like to do. So in actual operation, competitive interests again lead to a divided research structure.

A second area of conflict with consortia goals is in the assignment of research personnel.[141] The consortia and the firms negotiate over the necessary skills for advancing the research, but the firms generally decide on the particular individuals. More importantly, from the perspective of the consortia, it is generally desired that the researchers remain as long as possible so that the learning that is acquired during the first few years is not lost due to a personnel change.[142] However, from the perspective of the firm, it is desired that useful know-how developed by the researchers be integrated into the company's own research in a timely manner. And finally, from the perspective of the researcher, an extended absence from the firm can be a handicap to one's career as one is removed from work that is considered closer to the key interests of the firm or its profitability. Thus an absence of longer than two to three years is less desirable for one's career development. In

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[141] Firstly there is the practical problem of cost reimbursement. The Key Technology Center only reimburses the firms for the direct salary of the dispatched employee, so the firm is left the burden of all overhead costs such as housing and benefits. To the firms then, dispatching workers means adding to its costs.

[142] Dr. Ai and others have commented that two to three years is often the minimum needed to become well versed in research in the technology.

the case of the planning for this project, as well as in most of the Key Technology Center projects,[143] the cooperative yields to the more competitive interests of the participants.

- *Organizational Summary*

In all cases we see that some communication between firms did occur, but was centered around the formation of the project. The planning and learning process appears to have provided the greatest opportunity for cooperation. At this phase of identifying what needs to be done, there is a level of uncertainty and ignorance which encourages mutual learning, again largely with public information. As the research progressed, and the firms became more confident about what they were doing, the flow of information between competitors diminished.

When the national laboratories are involved, we see that although they are primarily interested in their own research they serve important roles in program guidance and technology transfer. It is clear that the national laboratories are most interested in the use of the funds from the national projects to promote their own research in the area. They have general autonomy in setting their research plan and only need to "consider" the work that the firms have been assigned.

Therefore the project budget received is a major boon for the national laboratory researchers. Recall also that their staff costs are supported by the regular laboratory budget, and that equipment funds are normally very tight in the usual operating budget. Thus funds received for participating in a national project can be used almost solely for the purchase of new laboratory equipment, which makes them very happy as they can better pursue the field as they feel best.

In the case of the Josephson junction project, we saw that ETL made an important technical contribution to the work of the firms with its development of more workable Niobium alloy junctions. However this type of contribution seems rare. Instead the laboratories serve the programs by providing a neutral position from which the progress of the firms can be evaluated, to a level at which the MITI headquarters staff could not come close to achieving, and by acting as an agent of information transfer between the firms. This latter role has particular potential when the research of the laboratories is evaluated highly by the firms, as ETL's work was regarding Josephson Junctions. The firms then

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[143] Gerald Hane, Government-Promoted Collective Research and Development in Japan-Analyses of the Organization Through Case Studies, PNL-7315, Richland: Pacific Northwest Laboratory, June 1990.

seek the laboratories advice, and this becomes an effective means of keeping informed about the progress of the firms.

The most important point here is that in the systems projects, instead of cooperation between competitors, we witness coordination between firms with complimentary interests. The lack of sharing in supposedly precompetitive research has also been observed by Luke Georghiou in his study of the Alvey program. He noted that "In Alvey, 70% of the participants worked not with their rivals but with companies that had complementary skills."[144]

Competitors in the market largely remain competitors in the project. But because the national laboratory researchers and university professors advising the project have access to information about firm advances, they act as information centers through which firms can monitor each other's progress. Competition thus has the positive effect of accelerating the pace of development as the firms try to keep up with each other. Instead of organizing for "precompetitive cooperation," we witness "*procompetitive coordination.*"

### Measures of project impact - the benefits to the firm and industry

In the end, what is important about the project is the extent to which it affects innovation. Companies will argue that these government promoted R&D programs have become increasingly peripheral as the firms have become much stronger and can individually support the research that they are interested in pursuing. They argue that participation is simply to keep the government appeased. By contrast, overseas we still frequently hear the comment that these government promoted programs have been central component of the advance of industries in Japan, enabling the country to leapfrog industrial levels in the United States and Europe. What we will find in the following analysis is that both of these statements seem largely incorrect when applied to the cases studies here. To understand this and to get a view of the range of possible impacts of the project on the technology and the industry I will approach the discussion in two levels.

At one level there is the impact of the project on the relative development of the specific technology. This is a narrowly defined view of the impact of the project, focussing on the level of development of the technology and the level of firm effort credited to the government program.

At a second level is the impact of the R&D project on the industry more generally and the markets. This is intended to be a much more macro level analysis which considers

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[144] Jane Bird, op.cit.

the size of the project relative to the activity in the industry in general, the impact the project seems to have in spurring similar R&D activity at other firms, the development of inter-firms relationships, the development of inter-firm networks and the impact on industrial diffusion, the development of complementary assets, and the impact of the technology in the market place. It is increasingly argued that it is these industry-wide effects that are the real benefit of the national programs, with the actual R&D projects simply being tools to achieve a general leveling up of the industry.

All of these projects are very recently completed or still underway, so the evaluation of their ultimate impact is certainly premature. However some useful comments can be made given the current relative level of advance of the industry.

### Impact on the firm and targeted technology

Have these programs had a significant effect on the firms and the development of the technology? By examining the contribution of the program to the level of research in the firms and the relative level of advance in the technology achieved, some perspective can be gained into this question.

What we learn is that in all of these programs, the level of technology is raised from one in which the state of the art in Japan clearly lagged the international frontier, to one in which it on par with or perhaps a step more advanced than international performance of comparable research prototypes. However advances are incremental rather than revolutionary.

This does not mean that all of the technological challenges which need to be met for market application have been overcome. In some cases, rather large barriers remain which need to be solved before there is any impact on the industry. Thus while the projects can generally be argued to be influential in leveling up the state of the technology they may be of little success in overcoming barriers to commercial penetration that have stifled researchers abroad.

#### - *Level of Activity Relative to In-house R&D*

For all of the cases investigated here, as well as for the cases in superconductivity described in the historical review, support from the government program represents a significant level of the firms overall participation in this area. There is, however, some separation in the level of parallel activity depending on the uncertainty of the technology and the ultimate commercial potential. As one would expect, the greater the potential markets and more moderate the uncertainty, the more moderate the government support. Where markets are more narrow or uncertainties high, the government plays a more major role. The levels of staff committed to the government project as a percentage of the staff doing parallel work are shown in Table 21. The Josephson junction project, HTS-ED, and QFP are all aimed at the same principal market, computer signal processing, and rank in extent of government support according to uncertainty.

Although the companies participating in each of these projects became increasingly wealthy over the 1980's, the level of government support still represented a significant share of the firm's activities in these technologies.

In the case of the Josephson junction, the government program accounted for 40 to 60% of each firms Josephson junction activity. It was closer to 40% before IBM dropped out in 1983, but did for a short time come close to 80% for some firms just after IBM dropped out. The exit of IBM caused some firms to largely abandon their in-house Josephson junction research, so MITI support was particularly important for certain actors in this period. Thus when measured by the level of in-house versus MITI project supported R&D, the MITI project is clearly influential.

For the firms, the continuing access to funds over the length of the project and the priority placed on this project as part of a national R&D activity gave research managers leverage internally to increase staff, and all companies did. In this area, all of the firms were relatively newcomers and all had relatively small staffs in the beginning. Fujitsu was considered the strongest of the industry at the time, but still only had on the order of 5 researchers. Project participation would allow firms to more than double this size. For firms, participation was a means of more aggressively addressing a weak activity.

In the Josephson junction project, it was also true that it was one part of a much larger high speed computer project which offered substantial funds for the industry participants. This project was another in a series of computer projects, and though company executives have increasingly discounted the importance this form of government aid as the they have become richer, the overall project still meant the availability of 23 billion yen that could largely go to research materials and equipment.

In the cases of the HTS-ED and the QFP projects, the level of in-house research is estimated to be somewhat smaller, reflecting the increased risk of the projects. HTS electron devices are poorly understood technologies, with the compatibility of the materials and the device designs very uncertain. Here the 10-40% is the percentage of all firm staff conducting work that is very similar. The QFP is a single device of unclear potential so we find it with the greatest level of support. Firms assert to be doing negligible independent

Table 21 Percent of Firm Researchers Conducting In-House Parallel Research in this Area[145]

| Technology | Percent of Parallel In-House Work |
|---|---|
| Josephson junction | 40 - 60% |
| HTS Electronic Device | 10 - 40% |
| Quantum Electronic Flux | 0% |
| Magnetoencephalograph | 30 - 50% |
| Superconducting Generator | 0 - 10% |

in-house research on this device because its high uncertainty only warrants a limited commitment of staff, whether it is the firm or the government that pays.

The two systems projects also involve a substantial fraction of government support. This is largely because of the scale of the investment and the narrowness of the market.

In the Super GM case in particular, the goal is at least in part to achieve a social objective where semi-public organizations are the customers, so the government bears more of the burden of the R&D. Most of the research at these firms now relating to a superconducting generator is and has historically been supported by the government. In theme this is similar to the the linear motor car program described in an earlier section. In the linear motor car case, the customer is solely the government with the government in turn supporting virtually all of the development costs.

In all cases covered in this set of case studies, it seems that the funding provided by the government program is a significant fraction of that provided by the firms. As one would expect the greater the potential commercial market for the technology, or the more active the competition in its development, the greater the level of matching in-house research. In all cases, firms indicated that the length and stability of government support helps them maintain in-house support for similar research.

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[145] Recall that this is different from percentage costs as the companies are not fully reimbursed for the full costs of their employees.

### Displacement?

One might wonder, however, whether or not the government work is simply displacing private sector work that would have occurred in any case. In all cases there was some private sector R&D that preceded governmental participation, but it appears that in all cases the government work accelerated private sector involvement faster than would have occurred in the absence of a program: enhancement rather than displacement.

In the case of the Josephson junction project, we can see a significant increase in patent applications after the initiation of the government program in 1980. IBM's involvement was known well before this and there were no significant technical advances announced in the period preceding this rise to explain the effect as being from something other than the government program. This is further confirmed when IBM left the field in 1983. Some makers reduced their staffs to a point that the in-house work was largely supported by government funds. The continuing government program sustained in-house work.

In the case of the HTS-ED, the government project appears to complement in-house work and will sustain company activity for at a minimum, the term of the project. This latter comment is also true of the systems projects which would not likely be taken up because of their scale and narrow markets.

The one case where there is evidence of displacement is the ERATO parametron project. The principal firm involved, Hitachi, was cooperating with Prof. Goto on the development of the parametron before the start of the ERATO project. When the project began, Hitachi's in-house funding of the staff was simply replaced by ERATO funding of the staff. However the size of the effort increased 4 to 5 fold and it now took a higher level of visibility and administrative support in the firm.

### - *Level of Technology Relative to International Standard*

Seeing that these programs are influential in accelerating the level of effort directed to the development of these targeted technologies, we come to the next question of whether this has a significant technical outcome. Do the programs lead to significant advances in the technologies when compared against the international state-of-the-art?

Unfortunately for most of the projects selected for this systems and devices discussion, we can only talk about the expected place of the technology as the research is still underway. The Josephson junction project is the only one for which we have data on project completion, so I will focus on it for this discussion. The Josephson junction case provides an interesting example of a project which met most of its prototype device goals, but which will probably have little impact on its intended use in computing systems. The Japanese firms that participated emerged as international leaders in the technology, but with little prospect of applying the technology in supercomputers: the firms gained a technological strength but little industrial advantage.

As mentioned earlier, the Japanese program initially mimicked that of IBM, focusing on lead alloy based Josephson junctions. However, lead junctions had certain weaknesses.[146] Their electron tunneling characteristics could change over time when stored at room temperature. Elements such as In, Au and Bi, for example, can diffuse from other electronic components into the lead matrix, cancelling the Josephson effect. In addition, because lead is mechanically soft, the junctions failed easily when integrated into devices.

On September 23, 1983, two years into the MITI project, the field worldwide was given a surprise when IBM announced at a workshop on Josephson junction technology in Lake Tahoe, California, that it was suspending its large R&D program in Josephson technology.[147] IBM felt that rapid advances in semiconductor technology were reducing the comparative speed advantages of the Josephson junctions and IBM felt that it would be extremely difficult to design a cache memory for a Josephson computer.[148]

In the industry in Japan in general, patent application activity reflects this event, with a noticeable drop in submissions during the 1983-1984 period. This was seen earlier in Figure 3.46.

For the project participants this was a major unexpected event as the electronic giant that they were targeting to overcome dropped out of the race. During this period of crisis, it was unclear whether this part of the overall supercomputer project would continue. One maker reduced its in-house staff by 50% reflecting a lowered priority, and only Hitachi claims to have maintained a stable level of activity.

The question remained about whether it was wise to continue the current trajectory aimed at the technology of the industry's leader, when the leader itself abandoned the option. For the program to continue it was generally agreed that a revised approach was needed.

This is when some timely advise was provided by MITI's Electrotechnical Laboratory. ETL pressed for a shift in technological emphasis from the lead-based IBM

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[146] Hisao Hayakawa, p.48.

[147] Arthur Robinson, "IBM Drops Superconducting Computer Project," Science, Vol.222, November 4, 1983, pp.492-494.

[148] Hisao Hayakawa, p.46; and Arthur Robinson.

priority to the refractory materials. In contrast with lead-based junctions, refractory superconductors, such as compounds of niobium are mechanically hard, and thus exhibit higher stability and reliability. The problem to that time had been that attempts to manufacture junctions had been plagued by the fact that Niobium is chemically active and reacts easily with the insulating materials used in the junction barrier.

Researchers at Bell Laboratories had successfully produced refractory based junctions, and ETL further advanced this work, noting and demonstrating that some of this problem with reactiveness could be overcome through the use of barriers such as amorphous silicon, aluminum-aluminum oxide, or magnesium oxide, rather than the niobium oxide barriers which naturally form.

Researchers in Japan made the transition from a difficult electron beam gun film deposition technique to the more successful use of sputter deposition. Here the high melting temperature characteristic of niobium is overcome by the use of a physical processing technique. Ions of a nonreactive gas such as argon strike the surface of niobium splitting off atoms which then crash into the surface that is being coated. The accumulation of these atoms on the substrate leads to the creation of a thin film.

The problem with the oxygen affinity was also reduced through continued work in Japan. The problem was overcome through the development of very highly efficient vacuum systems and vacuum pumps.

In addition, Niobium-based materials are superconducting at higher temperatures which means greater stability and less sensitivity to temperature fluctuations, and these materials have larger gap voltages which means faster intrinsic switching. The Niobium junctions were also demonstrated to withstand the required process temperatures of several hundred degrees Celsius, whereas the lead-alloy junctions had to be kept below 100 C.

An important point here is that the internal inertia from the initial 9 year plan made continuing the project much easier than would have been otherwise possible if the firms were funding research on their own. Because the Ministry of Finance has little interest in the content of the R&D programs once they have been launched, and little ability to understand progress even if they had an interest, there were no strong budgetary pressures to terminate. The existence of the large scale project and its funding thus played an important role in allowing the continuation of research which may otherwise have died.

With the international leader out of the field and the major programs now existing because of this project, international attentional turned to Japan. And progress was made. Fujitsu succeeded in developing a 8 bit MPU based on Josephson junctions, Hitachi demonstrated a 4 bit MPU, and NEC developed a 4 K memory with an access time of 580 ps.[149]

By 1987, Fujitsu had developed a 4-bit microprocessor based on Josephson junction which it claimed was the first such device constructed in the world.[150] It's design was based on Advanced Micro Devices' Am 2901 microprocessor and operated with a total of 1841 gates. The clock frequency in the critical path was operated at a speed one order of magnitude faster than a GaAs microprocessor, 770 MHz, and consumed three orders of magnitude less power, 5 mW.[151]

This was followed in 1989 by the development of a 8-bit data processing system, essentially a microprocessor, which was constructed with 6,300 gates and 23,000 Josephson junctions. This device was tested with an average critical path speed of 5.3 ps and a speed of 7.0 ps per gate in the arithmetic logic unit. Power consumption was measured at 12 mW.

The latter Fujitsu development attracted particular international attention as it was the most advanced in the world when announced in February of 1990. The head of the Josephson activity in Fujitsu, Dr. Hasuo, recounts the extremely high interest in their development when he attended the International Solid State Circuit Conference in the United States in the middle of February. He was approached by 3 firms to give a more detailed presentation to a gathering of their staffs. A badly delayed flight, however, caused him to be close to five hours late for the meeting. But when he arrived he found that all 20 of the invited attendees were still waiting, and pressed him with questions for hours before they finally broke for dinner at 10:00.[152]

Hitachi's 4-bit microprocessor, also based on the Am 2901 design, was constructed with 1,800 gates and 5011 Josephson junctions. A clock speed of 770 MHz was also achieved along the critical path of the chip, along with a power consumption of 5 mW and a gate speed of 9 ps.

In addition, in 1989 researchers at MITI's ETL developed what they have asserted is the world's first Josephson junction computer, with the Josephson logic and memory

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[149] Program results are summarized in the program's final technical reports, <u>Ogata Kogyo Gijutsu Kenkyu Kaihatsu, Kagaku Gijutsuyo Kosoku Keisan Shisutemu no Kenkyu Kaihatsu, Keika Happyokai Ronbunshi I & II</u>, Tsukuba: Denshi Gijutsu Sogo Kenkyujo, June 1990, and briefly in K. Tamura, "Ogata Kogyo Gijutsu Kenkyu Kaihatsu, Kagaku Gijutsuyo Kosoku Keisan Shisutemu no Kenkyu Kaihatsu, Seika Gaiyo," Tsukuba: Denshi Gijutsu Sogo Kenkyujo, June 1990.

[150] S. Hasuo, "Josephson Digital and Analog Devices with Niobium Junctions," 1st International Symposium on Superconductivity, August 28-31, 1988, Nagoya, Japan.

[151] S. Hasuo, "Josephson Digital and Analog Devices with Niobium Junctions."

[152] Akira Nakajima, "'Hi no Maru,' Jyosefuson Densanki - Kaigai de Takai Houka Eru," <u>Nikkei Sangyou Shimbun</u>, March 8, 1990, p.5.

devices successfully integrated.[153] The computer, known as the ETL-JC1, used four Josephson junction based chips, was constructed with a total of 22,000 Josephson junctions, and combined to deliver a 1 kilobit RAM and 1280 bit ROM. It operated at a speed of 1 KIPS with a power consumption of 6.2 mW.

When compared with the technical goals posed at the outset of the program, program supporters can advertise technical success. However, memory remains an unsolved challenge for large scale computer applications of the technology. Fujitsu was initially assigned the task of developing a cache memory and NEC a mass memory, but in the middle of the project Fujitsu largely abandoned this activity. Then NEC switched emphasis from mass memory to cache memory, realizing that the latter would be needed for actual computer operation. When this again proved to be difficult, they switched the focus back to mass memory, allowing the achievement of the program goals, but still leaving the challenge of the most difficult technology unsolved.

Thus, the program seems to have lead to the dreaded technological dead end - at least for the foreseeable future. For the JJ project to have been considered an overall success it would have to have been the technology of choice in developing the high speed computer prototype. But it still isn't.

However a more important reason is that other advances in computer processing appear to have made the Josephson junction a far less attractive option than it might have been at the outset of the project. This will be described further in the following section discussing the impact of the projects on the industry more generally.

A second project just completed is the Goto QFP project.

By 1990, researchers in the magnetic shielding team had succeeded in at least partially overcoming the greatest challenge in the development of this technology - moving the trapped flux through local laser heating. This is a step that had evaded Prof. Goto from the outset and proves, he asserts, the practical feasibility of eventually eliminating the flux and achieving a perfect magnetic shield. By 1990 they had also achieved a switching speed of 8 GHz, approaching the 10 GHz they hoped to achieve through their computer simulations.

After the project is completed at the end of September 1991, the work at Hitachi will continue under an equipment use agreement with JRDC. JRDC will not provide funds to Hitachi, but will allow the firm to use the equipment bought by the ERATO project for an additional two years.

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[153] "Agency lab develops prototype for next generation computer," Japan Economic Journal, December 12, 1989.

To continue the research, the returning Hitachi researchers will be joined by three of the project research who came from universities. All three will have received their Ph.D.s as a result of the research they pursued. Thus for Hitachi, the project functioned as a very effective training and recruitment vehicle.

Finally in May of 1992, JRDC will reinitiate support in the form of a High Technology Consortia, with Hitachi and ULVAC joined by several other firms to continue the development of the QFP.

In the case of the parametron, although some research by IBM, Hewlett Packard, and the University of California at Berkeley is underway to explore this technology, there has not been any indication in the literature that they have advanced beyond the accomplishments of this project. So a relative comparison has little significance as the project was form the start the most advanced in this technology.

In the case of the Super GM project, the primary incentive for participation appears not to be the technology development itself, but the market possibilities that successful prototype demonstration would create. Should the electric utilities ever adopt superconducting generator technologies, it will only be after the successful demonstration of a prototype which is of a scale relevant to commercial use. This is the opportunity provided by Super GM. Thus participation in Super GM becomes a key to participation in the eventual commercial marketing of this technology, and the firms that participate will create for themselves, to some extent, a barrier to the entry to other firms who will lack the experience and salience gained through the project.

Here, technological demonstration alone is not sufficient to describe the value of the outcome. For example, Hitachi's internally developed 50 MVA superconducting generator is fundamentally the same as the 70 MVA quick-response generator that it is assigned in the program. Clearly, Hitachi could develop a 70 MVA prototype if that is what would be necessary to market the technology. But it is not sufficient. The utilities have to want to buy, and one of the roles of MITI participation is to provide encouragement to view this technology favorably. Although all of the utilities are nominally private, recall that they are all closely administered by MITI's Agency of Natural Resources, and the agency has substantial regulatory and licensing powers. Hence if the utilities are further encouraged through a MITI program to consider a new technology, the depth of the consideration deepens.

## Impact on the industry

Although the technical goals represent the nominal targets for projects, there are a range of other possible effects which might importantly influence the development of this area in the technology in the industry generally. There are a number of collective benefits that can arise from these programs, and in this section the following possibilities will be discussed: 1) market effects - the impact of the technology in the market place; 2) diffusion effects - the development of inter-firm networks; 3) complementary asset effects - the development of needed supporting skills or industries; 4) alliance effects - the development of inter-firms relationships; 5) signaling effects - other firms entering the field because of the national project; 6) spin-off effects - the benefits of unanticipated uses of the technologies developed, and 7) competitive effects - the enhancement of industry competition.

The most important of these is the competitive effect. It is the strengthening, or "leveling up" of major competitors to international levels which is the greatest benefit competitors of the programs. The programs not only help to launch the firms, but do so with the intention of positioning the firms to continue to accelerate development into the market.

### Market effects

One important measure of the ultimate success of a development project is the extent to which the knowledge or technologies developed are used. As all of these projects are still underway or only recently completed, the conclusions and inferences can only be tentative. Nonetheless, comparison with the state-of-the-art during the project's execution or at its end can still give some insight to its contribution to ultimate end uses.

Returning to our discussion of the Josephson junction, we can see that what seems to have ultimately led to the demise of this option as an important technology for the supercomputer is related more to advances in competing technologies.

Even though the devices themselves have seen notable development over the decade they suffered from three problems that frequently arise in R&D: 1) more complexity than anticipated, 2) rapid parallel development of competing hardware, and 3) development of other technologies which obviate the advantages of the Josephson junction. All three reasons were cited by IBM in 1983, at the time of its decision to stop their Josephson junction program.

The problem of technical complexity refers to the intrinsic difficulty of making a cache memory with Josephson junctions. In LSI memory, cells are typically lined up in columns and rows with the signals driven by the voltages of the switching devices. However, Josephson junctions are not capable of generating large voltages because of their nature, so they are inherently handicapped in driving large memories. The 4 KB mass memory developed by NEC meets the project goals, but is still a long distance from the 4 MB silicon memory chips that it is currently selling.[154]

The second problem for Josephson junctions was the rapid improvement in silicon and galium arsenide semiconductor devices. In the late 1970's the switching speeds of silicon semiconductors were on the order of 100 to 200 picoseconds. However by the late-1980's, semiconductors were recording speeds in the few picosecond range, not much different from Josephson junctions. From the beginning of the project it was realized that galium arsenide semiconductors had the possibility of performing near the speeds of Josephson junctions, and developments though the decade both within the program and externally proved this to be possible.

Finally, there was the successful development of higher speed parallel processing systems for the high speed computer. In America, for example, N-Cubed had developed a parallel processing system based on conventional silicon technology that had a computing speed of 25 Giga-FLOPs. In 1990, a consortium led by Intel Corporation and the California Institute of Technology announced that it had developed a supercomputer using parallel processing and novel "mesh-routing" chips which could perform an average of 5 to 15 Giga-FLOPS, with a top speed of 32 Giga-FLOPs.[155] Both exceed the program's nominal goal of developing a 10 Giga-FLOP machine.

These three problems for long-term planning can also be used to help place perspective on the potential of the other programs. The Goto QFP technology still seems to face all three of the barriers faced by the Josephson junction. The physical device has yet to be fully demonstrated, advances in switching devices are reducing the difference in speed, and advances in computer system architecture and reducing the overall computing advantage.

The systems projects appear to face smaller technological barriers, but still face the challenge of being superseded by parallel developments in related technologies. For the superconducting generator this threat would come in the form of even greater reliability in already efficient conventional technology. With reliability weighed heavily by the utilities,

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[154] Akira Nakajima, "'Hi no Maru,' Jyosefuson Densanki - Ogatakeiki no Shuyaku no Seki Toku," Nikkei Sangyo Shimbun, May 9, 1990, p.4.

[155] "World's Fastest Computer," Science, November 30, 1990, p.1203.

penetration if it occurs, may be very slow. In the case of the sensors, no other technologies currently known to be under development have the potential of producing the same resolution. However, with an increasing number of firms investing in this and related technologies, it may not end up offering substantial advantages for patient diagnosis to parallel systems being developed outside of the project. Nonetheless, although the actual size of the market will depend to some extent on the cost and diagnostic capabilities of the system, the technology seems sure to have significant impact on the science of the user.

### Diffusion effects

We observed in the analysis of the high temperature superconductivity research programs, particularly in ISTEC, that R&D consortia can provide a forum for the diffusion of information and know how. Recall that some observers have proposed that this is particularly important in the case of Japan, where rigid labor markets prevent the exchange of information that attends personnel movements in more flexible markets.[156]

In these system and device case studies the diffusion of information, particularly between competitors, is not a regular or smooth process, and to the extent it does occur during the project appears to be due to the interdiction of a third party, the national laboratories. In the cases of the Josephson junction and HTS-ED project, cases involving the participation solely of competitors, we saw that the research was conducted in separate facilities with independent goals. In an attempt to promote communication between these firms, the consortia organized technical group meetings on the order of every two weeks to once every one or two months, depending on the size and extent of coverage. More than discussions, however, these sessions tend toward formal presentations, with the firms letting out what they feel that they are required to because of their participation.

A channel that they cannot control as tightly, however, is that of the national laboratories. Researchers in the laboratories have the formal task of evaluating the work of the firms, with formal evaluations at mid-project and its termination. More important for facilitating its role in diffusing important information is the laboratory's role as an evaluator and advisor. If the laboratory is strong in the technology, as ETL was in the case of the Josephson junction, firms will seek its advice and the laboratory will learn of firm

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[156] Gary Saxonhouse, Japanese Cooperative R&D Ventures a Market Evaluation, Seminar Discussion Paper No. 156, Research Seminar in International Economics, Ann Arbor: University of Michigan, August 1985.

problems and advances as it advises. The laboratory thus becomes a center point for the transfer of information, creating diffusion where is would not otherwise occur.

This same general argument seems to apply to competing firms that participate in the systems project.

Where there is evidence of a substantial amount of interaction between the competitors, however, is in the planning process. At this stage the firms are still in the process of learning about the state of the technology, with the planning taking an average of two years. Thus the most active phase in the diffusion of information seems to be before the project begins rather than after. It is in this planning stage that the diffusion argument among competitors is most relevant.

### Complementary asset effects

As one of the principal intentions of the systems projects is to establish links between a variety of technical skills, they are to some extend inherently exercises in building complementary assets. In the case of the Super GM project, for example, the program is designed to link the materials and component manufacturers with each other, and just as importantly with utilities which would eventually adopt the technology if successful. The participation and co-optation of utilities is, as mentioned earlier, one of the principal purposes of this program, since the absence of their commitment would be a severe handicap to commercialization.

In producing the prototypes the supplier firms also upgrade their own technologies to better match eventual commercial requirements. For example in the superconducting generator, the cable and wire manufactures wanted to increase the twist pitch of the superconducting wires to accommodate the high fields required of the prototypes. Twisting a conductor about its axis causes the voltage between any pair of filaments to reverse periodically, greatly limiting flux jumping, also known as cross-matrix current. So they worked with a wire equipment manufacturer to extend the capability of current equipment.

In the cases of the Josephson junction and the HTS-ED, evidence of complementary assets being articulated through the programs is less clear. One outside advance which did prove very helpful was in sputtering technology in the late-1970's and early-1980's. Surface science techniques in general advanced rapidly in this period and the advances made in sputtering enabled the difficult manipulation of niobium-alloys into workable junctions.

Generally, however, in these cases the devices are discreet and do not require the supporting skills of the systems technologies. For use in their intended applications, integration with large-scale computer designs is of course essential, but these skills are also held by these same firms, as they are all large integrated manufacturers. Thus as the skills for development, for integration into final products, and for sales are all contained within each of the participants, the need for developing important complementary assets was not critical and did not evidence itself.

### Alliance effects

Studies of the European Community programs in cooperative research such as EUREKA and BRITE by researchers such as Georgio and Sipriano have noted that an important benefits firms receive from participation is from the opportunity to form inter-firm alliances for the development, production, distribution or sales of products which may or may not be related to the topic of research. One might expect to see joint ventures between vertical or diagonal interests or cartels formed by firms in the same industry.

Because these programs tend to be limited to large companies that already have a strong presence in the economy, however, the chances created for truly new opportunities do not appear significant. In vertical and horizontal relationships, many of the larger firms are already involved *keiretsu*, which limits their freedom to form new alliances in Japan. This would be particularly difficult with a member of another *keiretsu* firm.

The case of Super GM showed that the power of *keiretsu* affiliation finds its way into the organization of the program, with Hitachi Cable only supplying Hitachi, Ltd., and with the primary cable and wire manufacturers in this project intentionally selected as those not affiliated with an industrial grouping. However, one can argue that the project allows for a smoother coordination between a number of component developers and a number of systems developers which should accelerate actual system development, and that firms not in *keiretsu* can firm their penetration into various *Keiretsu*. These claims can also be made for the superconducting sensor project.

The cases of the Josephson junction and HTS-ED projects showed little evidence of desire to collaborate by the participating firms, with little evidence that the projects are feeding the growth of cartels more than competitors.

Thus strategic alliances, at least through the systems and device projects studied here, are not a significant benefit because of the small scale of the market and participants. The projects do, however, allow for some non-*keiretsu* penetration into the *keiretsu* system.

## Signaling effects

Signaling effects were seen to be present in our earlier historical discussion of the development of the superconducting magnets for the MHD generator and in the early years of the superconducting electric generator. We saw firms which were not participating in the government programs, such as Fuji Electric and Fujikura in the case of the MHD project, and Hitachi and Toshiba in the case of the superconducting generator, initiate technology development programs in response to the government sponsored projects, either with the intention of joining the project later or of being prepared should a market begin to appear. But this was in the early years of superconductivity when it was not clear what uses carried the most potential.

In the case of the projects investigated here, however, clear evidence of signaling is not clear. In most of these cases the firms who came to be involved in the technology were involved before the start of the government program, and there is no evidence of purely private sector programs challenging the government programs in scale of investment. Patent and publication data from the Josephson junction project shows that the primary industrial actors were those sponsored by the government project.

In the case of the magnetoencephalograph, the principal firms in the small Japanese industry are those which helped to create the project. The technology was certainly generally known by the medical equipment industry generally. However, during the period of project formation and execution, a number of other firms have begun development programs, including Fujitsu, Furukawa Electric, Mitsui Metals, Sumitomo Heavy Industries, and NGK Insulators. The existence of a multi-year government program to propel this technology was cited by several of these firms as an important factor in committing resources to its in-house development.

It seems that as the industry has matured, it became much more capable of evaluating promising applications of superconducting materials and would move to these areas more quickly, before there were any government programs. An example of a technology area that has grown very rapidly without a government program is that of Magnetic Resonance Imaging (MRI), which is superconductivity's largest international market.

The government has increasingly come in after the industry has conducted preliminary development and clarified the international markets and competition. So if there is signalling now, it seems to be from the industry to the government.

## Spin-off effects

Another argument which has gained wide circulation is that the prototypes which embody the formal goals of the programs are really just vehicles for the firms to increase their skills in this technology. The ultimate benefits comes when the firms apply this experience to more advanced, commercially tailored versions of the technology, or to other technology areas. Spin-off, it is argued is an important benefit of these programs as they are generally intended to be "technology base" rather than product specific.

In the cases studies there does seem to have been an important spin-off effect, but for other reasons. Spin-off benefits from the programs stem from 1) the market for superconducting technologies which the projects create, 2) the maintenance of a competitive capability in superconductivity which can be directed to entirely different end-use technologies, and 3) the existence of a research fund that can be drawn from to support unanticipated events in related areas such as the discovery of HTS.

In the early superconductivity projects we saw that the market that was created by government procurements was the principal one companies addressed in developing superconducting magnets. When Richard Brandt visited Japan in 1971 for the Office of Naval Research, he concluded that the national program in MHD had provided a critical market for the development of the superconducting magnet industry. "In the absence of these national projects," he observed, "there is not enough demand to sustain the many companies involved."[157]

The development of the linear motor car, of fusion test facilities, and of the various electric generator prototypes, and the high field test facilities being created as part of the Multi-Core Program, all contributed to the support of this market for magnets in the ensuing years. Largely to the credit of this pull from demand, a number of cable and wire manufacturers were able to sustain development activities in superconductivity and have today emerged as strong international competitors.

Secondly, there is the maintenance of a general competitive capability in superconductivity. As a result of this general capability, the industry was well positioned to advance into the unexpected use of technologies such as MRI. The experience of Japanese firms in superconducting magnets was clearly a benefit in assisting their quick entry into this field.

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[157] Richard Brandt, "Superconducting Technology In Japan," ONR-28, Arlington,VA: Office of Naval Research, June 1971, p.2.

Thirdly there is the research budget that was made quickly available after the discovery of HTS. Recall from our earlier discussion that the rigid government funding system presented new programs in HTS research from being started until a year and a half after the confirmation. MITI did, however, have other LTS projects underway and was able to divert some of these funds to support HTS work. In both the Josephson junction project and the Super GM project, funds were reallocated to support tasks in HTS. In the case of Super GM, for example, seven research tasks were defined and assigned to seven different firms: Furukawa, Hitachi Ltd., Toshiba, Fujikura, Mitsubishi Electric, Sumitomo Electric, and the Japan Fine Ceramic Center (JFCC). The tasks are summarized in Table 22. JFCC was added to the program solely to conduct research on these oxide materials. Total funding for the HTS tasks was on the order of 3-5% of the total project budget, and all research was conducted separately by each of the laboratories, not cooperatively.

However, more direct spin-off from the project technologies seems a more dubious claim. The promoters of the superconducting sensor project, for example, are leveraging the spin-off argument to justify support, noting that the technologies development for ultra-magnetic sensing may find important uses in functions such as non-intrusive inspection of structures, materials research, or the analysis of signals in computers.

A clearer example is seen in the Josephson junction project. Here the spin-off argument is being presented by supporters as evidence of the breadth of benefits stemming

Table 22 HTS Research Tasks Assigned to Participants in the Super GM Project

| Technical Task | Firm |
|---|---|
| Wire forming techniques | Furukawa |
| Large area construction | Hitachi Ltd. |
| Non-uniform response technology | Toshiba |
| Machine applications | Fujikura |
| CVD processing | Mitsubishi Electric |
| Melt processing | Sumitomo Electric |
| Ultrafine particle ceramic wires | Japan Fine Ceramic Center |

from this technology. But these arguments appear to be more a post-hoc justification rather than a convincing assessment of serendipity.

The Nikkei Sangyo Shimbun reports that when asked about near-term applications of Josephson junctions, researchers now focus on uses other than the originally intended supercomputer switching such as 1) computer accelerators to upgrade conventional silicon computers to speeds nearing that of a supercomputer, 2) uses for which parallel processing cannot manage such as sensing fast serial signals emitted by the birth of stars, and 3) SQUID sensors for medical use.[158] In the near-term, the biggest market for Josephson junctions appears to be in Data Signal Processors used by the military. This is far from the initial visions of the program at its outset, and appears to reflect an attempt to salvage value once the primary target appears unattainable.

Spin-off thus seems to have been important for the technology markets created by the projects, *for sustaining a general capability that could be turned to* commercial opportunities, and for providing a sources of funds to quickly initiate some HTS research. Important spin-off directly from the project technologies has yet to be witnessed, and in the one case where it was asserted, it appears to be retrospective justification more than a description of true benefit.

## The Competitive effects

Fostering competition during the conduct of the program, and then fostering the development of commercial competitors in the technology area is among the most important benefits of these programs. We saw earlier that by having a number of firms pursuing similar strategies, the consortia benefited from the sense of competition between developers which acted to enhanced the speed of the development process. As commercialization draws near, the influence of competition can become far more pronounced as firms race to obtain return from their research investment. It is in the creation of these competitors where the research projects seem to have a significant influence.

Note that in all of the projects, an average of at least three firms were selected to develop the principal technology as well as many of the component technologies; and note further that these firms are among the most commercially successful in their industrial sectors. We can recall from our review of the linear motor car that three cable and wire manufacturers were selected to develop the magnets and electrical infrastructure, and three

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[158] Akira Nakajima, "'Hi no Maru,' Jyosefuson Densanki - Ogatakeiki no Shuyaku no Seki Toku," Nikkei Sangyo Shimbun," May 9, 1990, p.4.

systems manufacturers were selected to develop the superconducting systems and the test vehicle. In Super GM we see three generator manufacturers developing separate systems, with the superconducting wires being developed by four cable and wire manufacturers. In the superconducting sensor project there are five developers of advanced medical imaging equipment with experience in superconducting equipment and sensors. And in the Josephson junction and the HTS-ED programs, we saw three and so firms working in parallel, competing, to eventually enter the same product markets.

In the case of the Josephson junction project, at the outset of the project the three principal firms had very little experience with this technology - they had very few patents and were far behind IBM. But by the end of the project, the three, which are among the world's leading electronics firms, are now among the leaders in Josephson junction devices. Recalling that these firms were selected because of their financial, marketing and technological strengths, the result of the program is that each of these firms is equipped with a capability that would likely not exist without the government project. It has created a small resource of Josephson junction specialists in firms which is estimated to total between 50 and 100.[159]

In both of the systems projects we see a similar building of competitive expertise. The project will create three generator manufacturers with the capability to develop commercial scale generators on their own initiative, placing each of these firms in a very good position should utilities in Japan and in other countries decide to embrace the technology.

In the case of the sensor project, the project will give four of the nation's leading medical device manufacturers experience in developing a technology with greater performance capabilities than any of its international competitors. It will take these firms from a position in which they are still technologically trailing firms in the United States and Europe in terms of performance, and place them in the lead. Each of these firms can then, again, commercially promote the technology on its own in the international market.

Thus through the R&D program, the industry will find itself with at least three prominent firms with skills in a technology area that will be near or beyond the international frontier. With three firms, competition is encouraged and a monopoly is avoided. With three commercially prominent firms, the likelihood that good ideas will run into a dead end with the end of the research program is reduced.

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[159] Akira Nakajima, 'Hi no Maru,' Jyosefuson Densanki - Jitsuyoka ni Futatsu no Kabe," Nikkei Sangyo Shimbun, May10, 1990, p.5; and from my interviews with firm representatives.

The parallel firm strategy also avoids one of the problems that Luke Georghiou noted regarding the Alvey program in Britain. He observed that "Each partner tended to be providing an essential component, with the consequence that if one partner went out of business there was a strong chance of losing an essential part of the work."[160]

Here, Japanese organization marks a significant departure from that of government research programs in the United States. In typical U.S. government programs, contracts are let out to individual contractors with an emphasis on the technical capability of the contractor and little emphasis on the contractors commercial strengths. The assumption driving this style of contracting has been that if the idea is good, and is in the public domain, someone will pick it up. Thus one can find many contract research organizations involved in government research programs; organizations with strong technical expertise but no commercializing capability. However, history has shown that much more often than not no other firms will pick up the technology and the research will be shelved as final reports once the contract is completed.

In Japan this assumption is not made. Commercial strength is considered a key ingredient for successful commercialization, so all of the firms that are key to any of the projects reviewed here are very strong commercial competitors. Technology strength, while of course important, is considered part of the recipe which has allowed these firms to become successful, and is in any case insufficient. Technology development is not assumed to be a simple package which can pass hands between organizations at appropriate stages, but a process that includes production, and for which production knowledge is integral.

This again reveals the "procompetitive" strategy taken by the programs in Japan. During project development, mutually beneficial links are "coordinated" between system developers and their suppliers to develop the needed complementary assets. But the primary systems developers are competitive among themselves, and this competition accelerates development. If successfully advanced, the projects position several strong firms and their suppliers for competitive entry into the market. "*Procompetitive coordination*" is the major value of these programs, not "precompetitive cooperation."

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[160] Jane Bird, "Britain Picks Wrong Way To Beat the Japanese," Science, Vol. 252, May 31, 1991, p. 1248.

## VIII. Evidence of General Cooperation in the Industry

What about cooperation occurring outside of the government program? In the previous two sections, I examined the role of government programs in promoting cooperation and innovation in high temperature and low temperature superconductivity. But this is only a portion of the collaboration that is occurring in the industry as it also occurs without government guidance.

In this section I will examine this autonomous collaboration to see whether these patterns reflect the influence of government programs or of structures of the industry. The principal questions investigated are the following.

- Does evidence reflect the use of collaboration for corporate diversification or the enhancement of a firm's position in the industry? Who are the collaborative partners?
- Does it reflect the influence of industrial structure or prior industrial relationships? In trade *keiretsu* have been shown to have a distorting effect on the market,[161] is this also true of innovation in this field? Data which exists for industries generally says that this will not be the case.[162]
- Do universities play a significant role in cooperative R&D? Conventional wisdom about Japanese universities is that they do not produce state-of-the-art work and are removed from the needs of the industry.
- Does collaboration reflect prior participation in government projects? Studies of the cooperative R&D projects in the European Community have indicated that an important contribution of the projects is to act as a catalyst for forming relationships and networks.

As mentioned earlier, following the confirmation of HTS there was a dramatic increase in the number of patent applications submitted in superconductivity. The total number of applications increased from 835 in 1986 to 6,237 in 1987 and 3,305 in 1988. Cooperatively authored patent applications also increased from 35 in 1986, to 237 in 1987, and 160 in 1988.[163] Of these collaborations in 1987 and 1988, projects in HTS represented 60% of the total in both years.

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[161] Edward Lincoln, Japan's Unequal Trade, Washington, D.C: Brookings Institution, 1990.

[162] Kikai Shinko Kyokai Keizai Kenkyujo, Tokkyo Shutsugan Shutai Oyobi Shutsugan Keitai kara mita Kikai Kogyo ni okeru Gijutsu Kaihatsu Katsudo no Bunseki, Tokyo: Kikai Shinko Kyokai, May 1984.

[163] Survey data was taken but the memory of firms is highly variable and not necessarily reliable, to the data has not been included here. The general magnitude and general trend toward diversity do not contradict the patterns suggested here.

## Diversification

One use of cooperation is as part of a strategy to enter a new field. By examining the patent applications we can see whether firms that use cooperation are indeed diversifying into the field or whether they are firms which are already strong in this field and are enhancing their strengths. We can also examine whether these firms turn to other firms, to universities or to other public institutions such as government laboratories or utilities.

Signs of diversification through cooperation appear when we examine the general change in activity before and after the confirmation of HTS. If we calculate the ratio of cooperative to independent patents for individual organizations, we find two groups at the top of the list: 1) public organizations and 2) firms new to superconductivity. Public organizations consistently had the highest ratio of cooperative to independent patents, with seven utilities submitting solely cooperative patents. At the top of the list were organizations including Riken, Dengen Kaihatsu, JRDC, and the Japan Atomic Energy Research Institute, with cooperative to independent patent ratios of 7.0, 6.5, 6.2, and 2.7.

More interesting for the issue of diversification, however, is the second group of firms, the firms new to superconductivity. Thirteen of the 14 firms with the highest cooperative patent application ratios were new to the field, with five submitting solely cooperative applications and the others with cooperative patent ratios ranging from 0.25 to 3.25. These firms include Showa Aluminum, Seisan Kaihatsu Kagaku, Neosu, the Fine Ceramics Center, Nippon Kokan, Nihon Soda, Showa Denko, Toa Nenryo, and Toshiba Ceramics. All of these firms have relatively small HTS programs and are trying to maximize their resources on entry. None of the major firms from the traditional superconductivity industry fall into this group of high patent collaborators.

For the next 36 organizations, cooperative patent submissions were a smaller percentage of their overall submissions, but nonetheless increased significantly with the arrival of HTS. Collaborative patent submissions in this group had increases that ranged from 30% to 98%, with all of the major LTS firms included. These traditional industry firms showed rather substantial increases in their submissions of cooperative patent applications, with the cable and wire makers consistently showing higher ratios than the systems manufacturers. Showa Cable and Furukawa had 90% and 85% increases in their cooperative output, and Sumitomo Electric and Fujikura had 65% and 60% increases. The systems manufacturers, Toshiba, Hitachi, and Mitsubishi Electric increased cooperative patent outputs 42%, 40% and 30% respectively. The relatively greater use of cooperation by cable and wire firms also appears in the relative ratio of cooperative to independent patents, with the main cable and wire firms generally showing ratios of 8-12% whereas the systems manufacturers generally had ratios of around 1-2%.

With these indications that collaboration is playing some role in the strategies firms are taking to come into superconductivity, I next explore the type of cooperation occurring, and look for evidence of differences in the use of this strategy.

First I will examine which types of partners are commonly selected by firms, and whether the choice of collaborative partners differs between the traditional LTS industry and HTS entrants. Figure 50 shows the distribution of patent applications among several categories of firm partners: other firms, government institutions, universities and utilities. The figure also separates the collaborations on low temperature metallic materials and those on high temperature oxide materials. These two pie charts show very different patterns of partner selection as governmental and firm partners were the most common for LTS projects whereas universities were by far the most popular choice for HTS projects. For LTS collaborations, 50% of the cases were with government institutions and 32% with other firms. Universities only represented 14% and utilities only 4%. For HTS collaborations, by contrast, universities represented 58% of the cases, with utilities following at 18% and firms and the government down to 12% each.

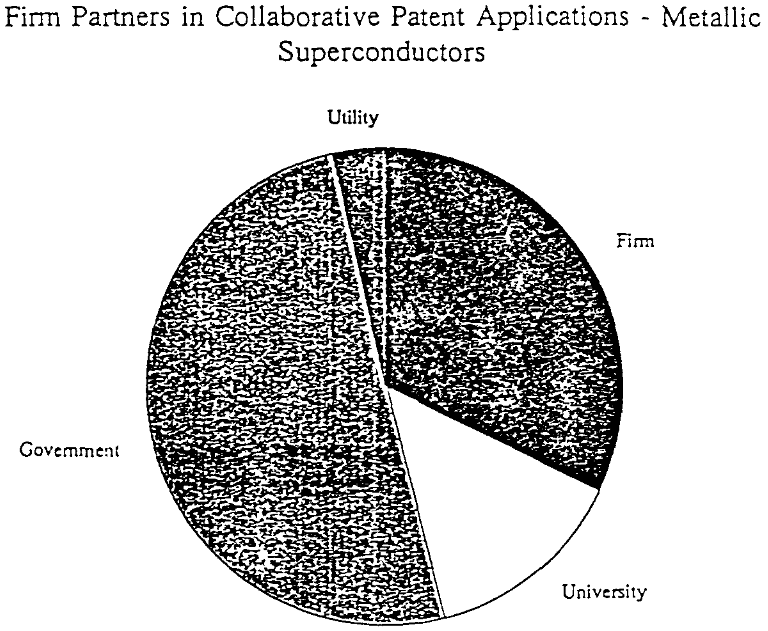
This division between categories of LTS and HTS partners becomes even more vivid when the comparison is made between each category of partner as shown in Table 23. LTS cases accounted for 83.2% of firm-firm and 89.2% of firm-government collaborations, whereas HTS cases represented 69.4% of firm-university and 72.9% of firm-utility collaborations.

The large percentage of firm-government collaborations in LTS is due to the long history of development of LTS magnets for government programs and government experimental facilities. We saw earlier that government programs have been main supporters and customers in LTS over the past 25 years, promoting the development of large magnets for new energy systems such as MHD, fusion, and superconducting generators, and the purchasing of magnets for experiments ranging in size from bench scale laboratory use to particle acceleration.

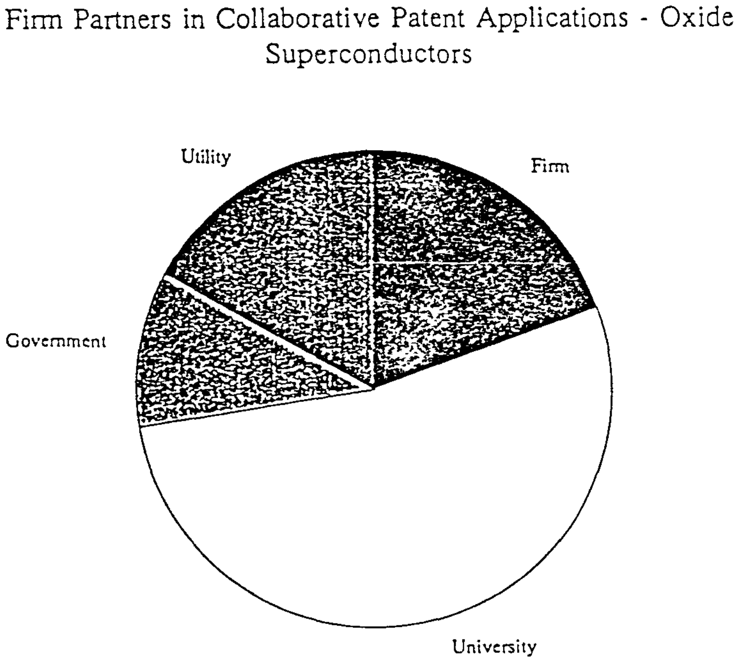
Firm-firm collaborations also reflect the history of LTS developments in Japan, of a stable but small market for suppliers, as well as inter-firm relationships which will be explored later in this section.

The large university presence in HTS collaborations reflects their often underestimated role as sources of frontier research from which the industry can learn. Here firms were benefiting from the change in Ministry of Educations regulations in the early-

Figure 50. **Firm Partners in Collaborative Patent Applications - Metallic and Oxide Superconductors**



Firm Partners in Collaborative Patent Applications - Metallic Superconductors



Firm Partners in Collaborative Patent Applications - Oxide Superconductors

Table 23. Patent Applications Separated by Category of Firm Research Partner and by Type of Superconductor

| | Metallic SC | Oxide SC | Pct. Metallic | Pct. Oxide |
|---|---|---|---|---|
| Firm | 144 | 29 | 83.2 | 16.8 |
| Government | 224 | 27 | 89.2 | 10.8 |
| University | 60 | 136 | 30.6 | 69.4 |
| Utilities | 16 | 43 | 27.1 | 72.9 |

1980's which has made such collaborations much easier than in the past. The cooperative activities of the universities will also be explored in more detail later in this section.

Lastly, the relatively larger emphasis on HTS collaborations by utilities is more a reflection of their recent entry into the active promotion of superconductivity generally than of any long-term vision which one might infer they held. The high level of utility collaborations in HTS is unexpected, and appears to be an instance in which, rather ironically, the conservatism of the industry is a principal cause of its tilted presence in HTS patent applications. Although prototype superconducting electricity generators have been developed over the past decade in Japan, there has been only lukewarm reception by the utility industry because of their concern over the reliability of the device and the impact on the system of introducing a new technology. Because of the size of the investment and the potential scale of any disruptions, the utilities have been very cautious in adopting new technologies.

It was just as the government and generator manufacturers had begun to convince utilities of the value of superconductivity, witnessed for example in the Super GM project, that HTS was discovered. Thus just as the utilities are beginning to favorably recognize research in a the field, they were struck by an unexpected event in which the priorities in the field are shifted to frontier research, and which as a consequence has them supporting the advanced HTS work more than they supported the developmental LTS work.

The degree of diversification can be further analyzed by adding one more variable : the newness of the firm to the industry. Because the superconducting industry has largely been cartelized by a small set of firms, it is easy to identify the main participants. By

Table 24. Degree of Diversification Through Various Modes of Cooperation, Represented by a Diversification Factor (DF)

| | All Superconductivity | Oxide Superconductivity |
|---|---|---|
| Firm/univ | 0.61 | 0.72 |
| Firm/gov't | 0.18 | 1.00 |
| Firm/firm | 0.23 | 0.66 |

calculating the percentage of the collaborations that were conducted with firms not established in the industry, an estimate of the extent of diversification occurring can be achieved. This percentage is represented by the Diversification Factor (DF) in Table 24. The Diversification Factor is on a scale of 0 to 1, with 0 indicating the in all of the cases the principal firms are from the established industry - a sign of core enhancement. At the other end of the scale, a figure of 1 indicates that all of the firms involved are from outside of the established industry - firms diversifying into superconductivity.

The table reveals striking differences in roles of collaborators for all superconductivity and for HTS cases. Although we saw in Table 23 that firm-government collaboration was weighted toward in LTS research, in the cases of HTS, all of the firm-government collaborations involved firms diversifying into the industry, not core-enhancing firms. A similar but less dramatic difference is seen in the case of firm-firm collaborations as well: when all superconductor activity is considered, the traditional firms dominate. However when the cases are limited to HTS, the greater presence of the diversifying firms emerges.

In the case of firm-university collaborations, we see that the universities tend to help the diversifying firms more in both LTS and HTS research, with a slightly greater influence in the latter case. University cooperation generally is the most likely made to be used for diversifying firms.

Finally, in all categories of HTS collaborations, we see that diversifying firms are more highly represented.

## Industrial Structure

By looking at inter-firm collaborations more closely, we can understand more about the structure of the industry. The discussion above has divided firms between those from the traditional superconductor industry and those diversifying into the field through HTS. In addition to "newness," there are other dimensions which might help to clarify patterns of cooperation. The dimension of greatest interest here is the influence of *keiretsu* or some forms of industrial grouping.

First we might ask whether membership in a *keiretsu* or a *keiretsu*-like organization (firms with equity holding in other firms) obviates the need for cooperation outside of the group. Or stated conversely, does exclusion from a *keiretsu* reflect in a greater need for collaboration?

In Table 25 the presence of *keiretsu* firms in each of the forms of collaboration is shown in a figure which is termed the *Keiretsu* Presence Factor (KPF). A high KPF figure generally, and for firm-firm collaborations in particular, reflects a strong presence by firms which are members of industrial groups.

With the discovery of HTS we can see that the presence of non-*keiretsu* members has increased slightly in universities, with the KPF falling from 0.94 to 0.70, and remains the same for firm-firm collaborations and government institutions. For firm-firm collaborations, at least one *keiretsu* firm is involved in about 90% of the collaborations. In firm-government and firm-university collaborations, *keiretsu* firms are still involved in about 70% of the joint patent applications. Thus *keiretsu* do not seem to substitute for the need to cooperate, at least with university and government laboratories.

However, in firm-firm collaborations, the question arises as to whether they are cooperating only within their group, diagonally across to firms in other groups, or between groups in the same sector.

Of the 173 firm-firm collaborations, 153 (87%) involve *keiretsu* members. Among these *keiretsu* cases we can then ask how many involve collaborations within the *keiretsu* and how many outside of the group. The patent application data show that 118 of the cases (78%) are in the same *keiretsu* or grouping and 35 of the cases (22%) are outside of the grouping. The tendency to stay within the group for patentable activities is thus seen to be rather strong.

Looking at the 23% of cases outside of the *keiretsu*, we can next ask what kind of collaborations these involve.

Table 25 Presence of *Keiretsu* Firms in Various Categories of Collaboration (*Keiretsu* Presence Factor, KPF)

| | All Superconductivity | Oxide Superconductivity |
|---|---|---|
| Firm/firm | 0.87 | 0.93 |
| Firm/gov't | 0.70 | 0.67 |
| Firm/univ | 0.94 | 0.70 |

Of these 35 cases, all except 3 involve diagonal collaborations. Eight are with firms in other identifiable *keiretsu*, 24 are with independents. Thus diagonal relationships are seen to explain almost all cases of collaboration with firms outside of a *keiretsu*. To keep the magnitude in perspective, however, it should be borne in mind that of the total of 173 firm-firm patent applications, only 18.5% represent cross-group diagonal alliances.

Next is the question of intra-sectoral collaborations, between competitors. Among the 173 firm-firm cases, only 20 involved intra-sector collaborations. Of these 20 intra-sector collaborations, two were projects managed or sponsored by utilities and one was closely tied to a government project. In <u>all</u> other cases of intra-sector cooperation involving a *keiretsu* firm, the participating firms were in the <u>same</u> <u>*keiretsu*</u> (four cases did not involve *keiretsu* firms.)

The strength of industrial groupings for patent generation can be further emphasized by examining the firms individually. The most salient case is that of Hitachi. Hitachi has the greatest number of collaborations in superconductivity of any organization and the greatest number of collaborators. However, if public or semi-public cooperators are excluded, then virtually all, 97%, of the inter-firm applications are with directly affiliated firms. This is shown in Figure 51. The details are presented in Appendix D, which shows that similar patterns are seen to exist with Toshiba, Mitsubishi Electric, and Furukawa Electric. Cooperative patent applications are either with public organizations, or, when they are with other firms, are largely intra-group. *Keiretsu* relations are quite strong in cooperative innovation in superconductivity.

For the other cable and wire suppliers, the patterns are somewhat different, with a greater reliance on public organizations as partners. The examples of Sumitomo Electric and Fujikura Cable are Also given in Appendix D. These data reflect the importance of the public laboratories as funders and users of this technology.

Figure 51. Patent Application Collaborators with Hitachi, Ltd. in Superconductivity

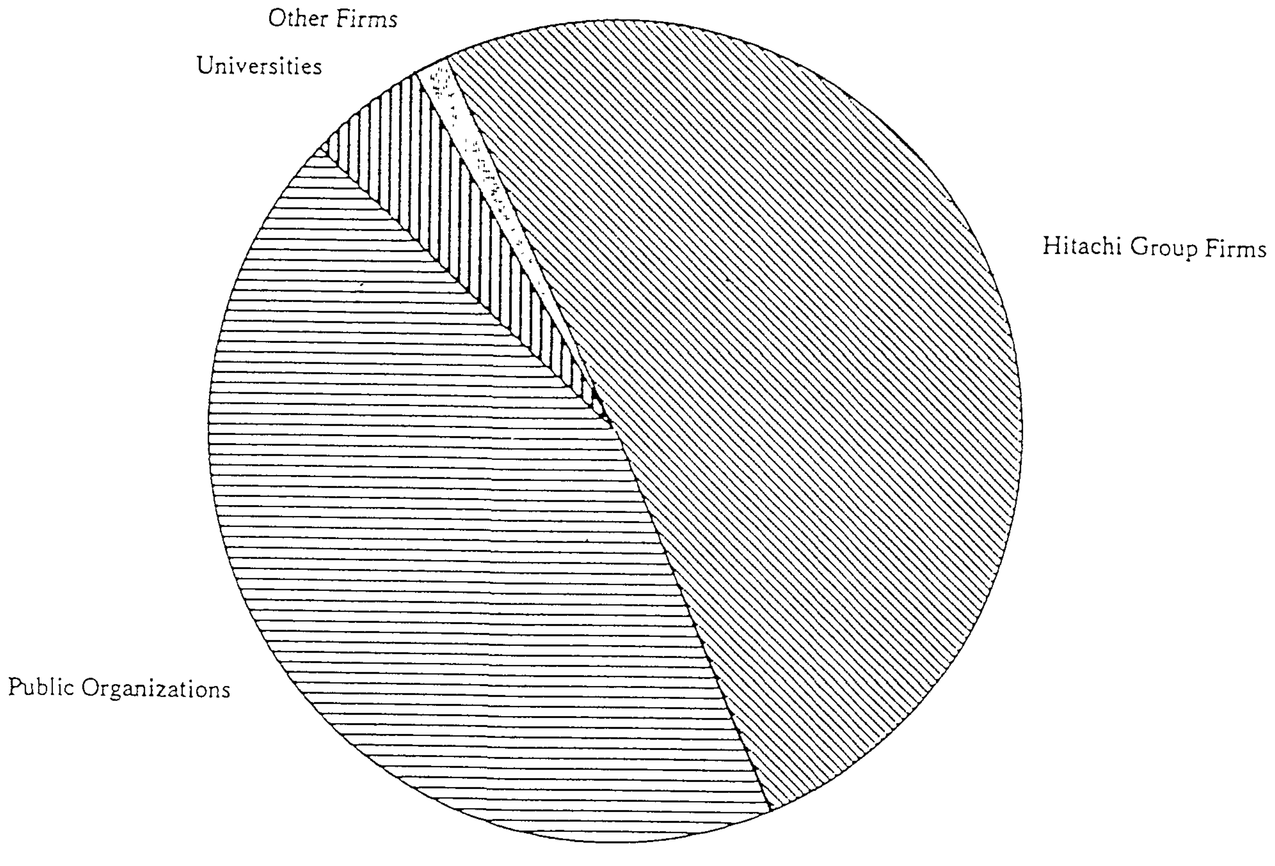


Table 26 LTS and HTS Collaborative Patent Applications of Principal Superconductivity Firms in 1987, 1988 and 1989

| | LTS | HTS |
|---|---|---|
| Fujikura | 2 | 32 |
| Furukawa | 11 | 29 |
| Sumitomo Electric | 12 | 4 |
| Hitachi, Ltd. | 42 | 13 |
| Mitsubishi Electric | 13 | 2 |
| Toshiba | 14 | 5 |

Earlier, evidence was presented that the level of use of collaboration differed between the cable and wire manufacturers and the systems manufacturers. We learn on closer examination that the difference is not just one of the range of partners, but also reflects a very different level of use of collaboration to enter HTS.

Table 26 shows that the three systems manufacturers and Sumitomo Electric continued to pursue most of their collaborative work in LTS technologies rather than HTS. By contrast, the other two major cable and wire manufacturers Fujikura and Furukawa increased the level of collaborative activity substantially in entering HTS. Collaboration for the product developers continued to focus on activities that were close to the existing market, which were LTS activities. By contrast, the firms that would be responsible for producing the first HTS products, the cable and wire firms, turned much more to collaboration to fill gaps in their scientific expertise.

Finally, if we turn to the question of who these firms collaborated with in their HTS research, the answer across almost all of the above firms is the universities. Twenty-three of the 32 HTS applications by Fujikura were with universities, 7 of Hitachi's 12 were with universities, and all of Sumitomo's, Mitsubishi Electric's, and Toshiba's collaborative applications were with universities. The sole exception was Furukawa which collaborated heavily with a utilitiy-related research organization (27 of its 29 cases.) Overall the universities accounted for 53% of the collaborative HTS applications among these firms, and the utilities 42%.

For this new area of science, it appears that the Japanese universities have had a significant role to play.

## Cooperation with Universities

In the discussion above, it was noted that university partners were used in the majority of cases of firms wanting to enter the HTS field. In this section the cooperative activities of the universities will be examined more closely to provide added insight to their contribution to firms and other research institutions before and after the HTS discovery.

Formally, there are four ways through which an organization can cooperate with a university. An organization can enter into a formal cooperative agreement, request specific research to be conducted on contract, donate to create a chair, or dispatch a researcher at the expense of the firm.

In this section I will explore evidence of university cooperation which confirms the contribution that universities make to industrial diversification as well as provide some perspective on the scope of university activity.

Because comprehensive statistics are not available from the Ministry of Education, I will use the data available on formal cooperative research agreements with universities, survey data from a questionnaire completed by 30 professors conducting research on superconductivity, and my survey of 60 firms about their in-house and cooperative research activities.

By examining records of all formal cooperative R&D agreements with universities, we find additional evidence of the contribution to diversification made by universities.[164]

One of the first points noticed about the cases of cooperative R&D is that the cases were well represented by both LTS and HTS collaborators. In the three-year period between 1987 and 1989 there were 41 organizations cooperating with universities in HTS and 26 in LTS.

Most of the collaborators in LTS were from the traditional superconductivity sectors, heavy electric machinery, cable and wire, shipbuilding (heavy machinery), and the utilities, with these sectors accounting for 81 % of the collaborations as shown in Figure 52. The majority of these collaborations focussed around new coil processing techniques and high field magnet designs.

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[164] "Minkan Nado to no Kyodo Kenkyu, no (Showa 62 Nen, Showa 63 Nen, Heisei Gan Nen) Do no Jisshi Hokyo," Monbusho, (1988, 1989, 1990).

Collaborators in HTS represent a much broader range of industries, also as shown in Figure 52. There is greater participation by firms interested in electronics applications and firms looking to diversify from their traditional chemicals, cement, and ceramics business bases. All of the firms involved are large firms, listed on the First or Second Section of the Tokyo Stock Exchange. Small and medium-sized firms have not selected this route to collaboration.

Of the forms of cooperation possible, individuals in the industry and universities cited cooperative R&D as the most troublesome because of the need to define boundaries and negotiate the division of proprietary rights. Cooperative R&D also means that the industry must make a contribution. As many firms diversifying into HTS were new to superconductivity and had relatively small programs, they were not in a good position to participate through this form of collaboration.

Rather than engage in a formal cooperative R&D agreement, most firms prefer to dispatch researchers for general training or to set up a contract research agreement with the professor and his students for specific research to be done. This later option was also seen as an important scheme for recruiting good graduates to the firms. Both of these routes were considered more straightforward.

Data on specific contracts and researchers dispatched were not made available by the Ministry of Education, so a questionnaire was sent out to professors involved in the three-year (1984-1986) Ministry of Education superconductivity research program. Thirty of the 60 professors surveyed answered, and all reported some form of collaboration with another organization.[165] Taking all of the cases between 1982 and 1990, Figure 53 shows that a little over half of the collaborating institutions were firms or private laboratories, about a quarter were universities, and the remainder were foundations and public institutions.

Collaboration in general, however, was at a low level until 1987, when the number of partner institutions increased from 11 to 37, as shown in Figure 54. The figure also shows the parallel increase in the number of visiting researchers from firms.

The largest cause for this increase was the growth in the number of firms, from 4 to 25. Collaborating firms came from a broad range of industries, again confirming the observation that universities played an important role in diversification. The sector distribution of the collaborating firms, primarily since 1987, are shown in Figure 55.

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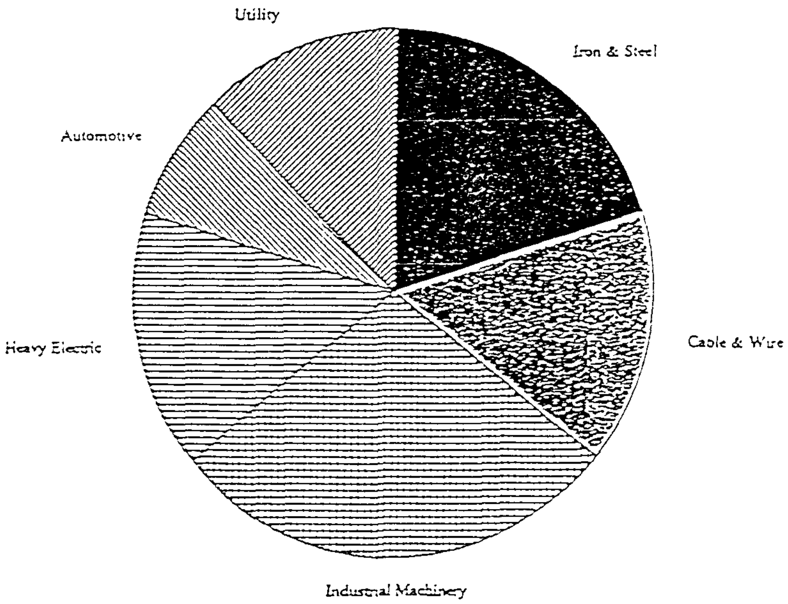
[165] Interestingly, only one of these 60 professors is also recorded by the Ministry of Education as hosting a formal cooperative agreement. This appears to be because of a difference in motives for the research. The MOE superconductivity program focussed on theory and new ideas, being centered in physics and physics-like departments. Those in the formal cooperative programs were all from engineering programs and were thus presumably closer to the needs of the industry.

Figure 52. University Collaboration in LTS and HTS Research through the Formal MOE Cooperative R&D Program

University Collaboration in LTS Research through the Formal MOE Cooperative R&D Program



University Collaboration in HTS Research through the Formal MOE Cooperative R&D Program

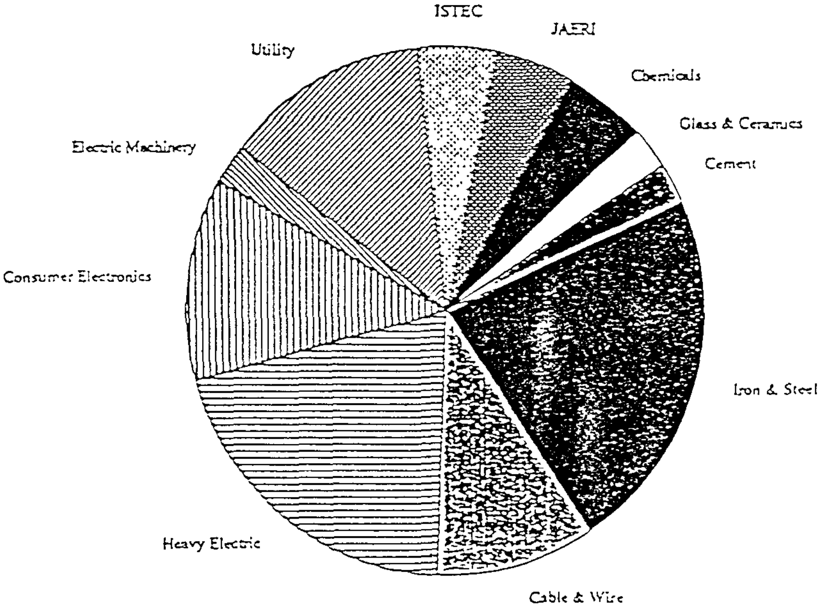
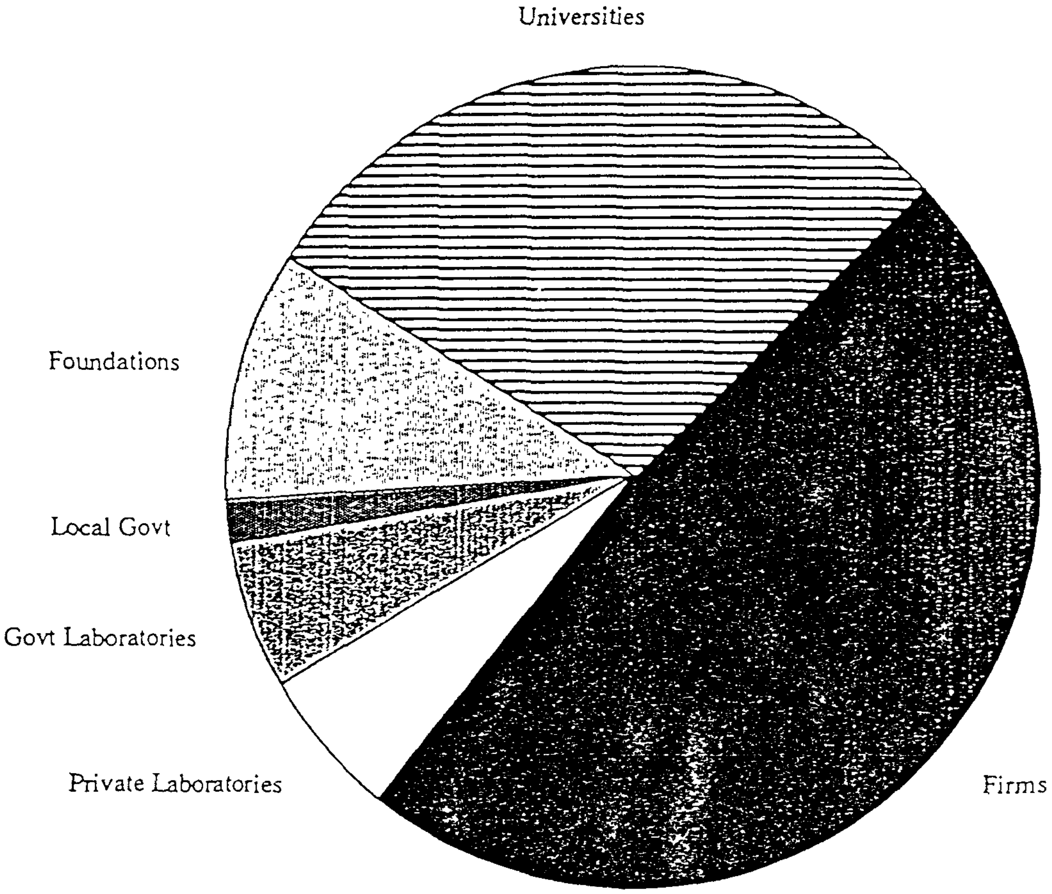


Figure 53. Types of Organizations Cooperating in R&D with Universities - From a Survey of 30 Universities



Finally, from the data above it becomes apparent that the collaborative research is focussed in the national universities and is not very well distributed among the private universities. All but one of the formal cooperative agreements with universities was with a private university, and all of the 60 professors identified as participating in the Ministry of Education program were from national schools. Research support to private universities is not a big part of the academic superconductivity world.

## National Project Spin-Off

One spin-off effect that government projects might have is to provide an opportunity for firms to identify mutual needs. Then, independent of the government projects, these firms could collaborate separately. Is there evidence of such collaboration?

The answer from the patent application data is no. Eighty percent of the firms that have participated in the same national project in superconductivity are firms cooperating with other *keiretsu* or group members, almost entirely Hitachi Cable and Hitachi, Ltd. Four other cases are diagonal cooperations which involve an integrated manufacturer, Furukawa, and a systems manufacturer, Fuji Electric. Only one is intra-sectoral. But even in this single case, Fuji Electric and Mitsubishi Electric, the research was closely tied to the work done by the government.

Participation in government projects did not lead to any evidence in patent applications of spin-off collaboration across industrial groupings.

## Summary

As conclusions are drawn about collaborative patent activity in superconductivity, it should be borne in mind that they represent only a small portion of the overall patent activity, ranging from 2 to 8% of total patents in any one year. The bulk of the innovation as reflected in patent applications is conducted independently.

The patent applications nonetheless provide indicators of the characteristics of collaboration, some of which are contrary to popular opinion and general industrial trends. It was revealed that the highest relative use of collaboration was by firms which are new to the field, which are diversifying into superconductivity. The relative use of collaboration among the established firms in the industry was uniformly lower, although this also increased significantly with their own diversification into HTS.

Figure 54. Number of Researchers and Universities Participating in Cooperative R&D with Firms - From a Survey of 30 Universities

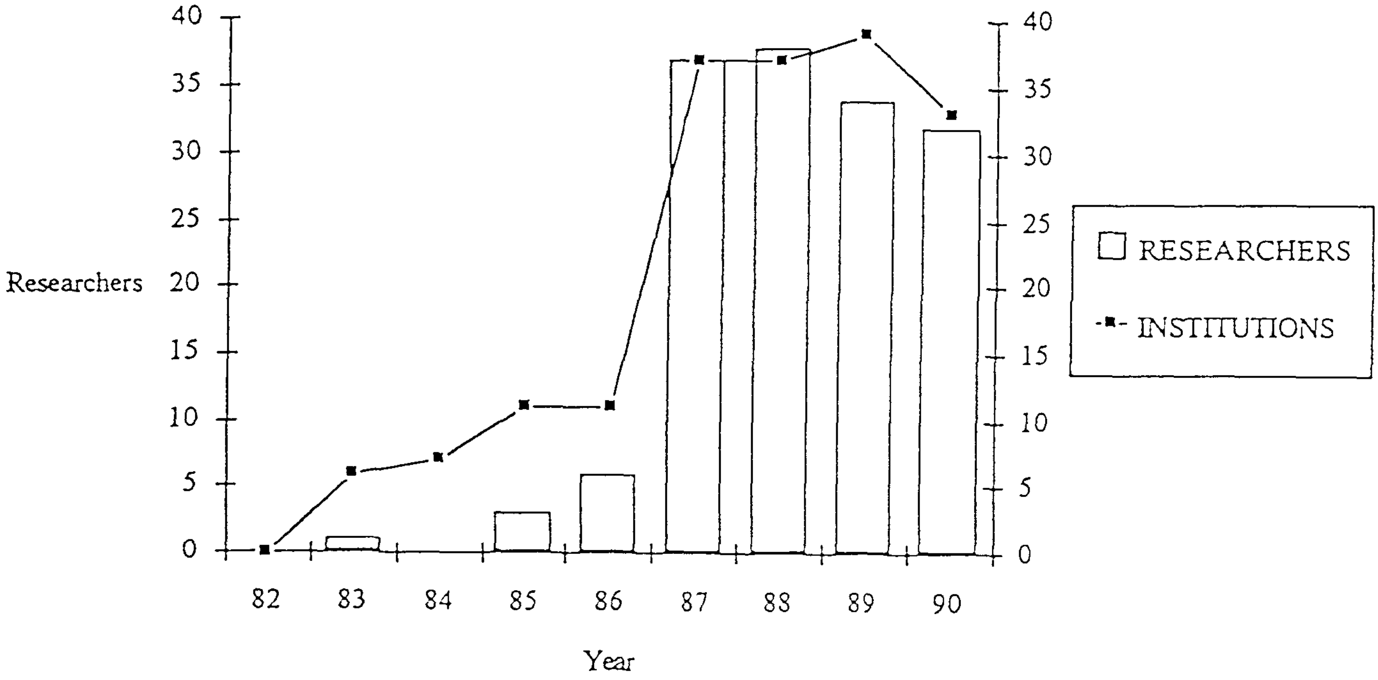
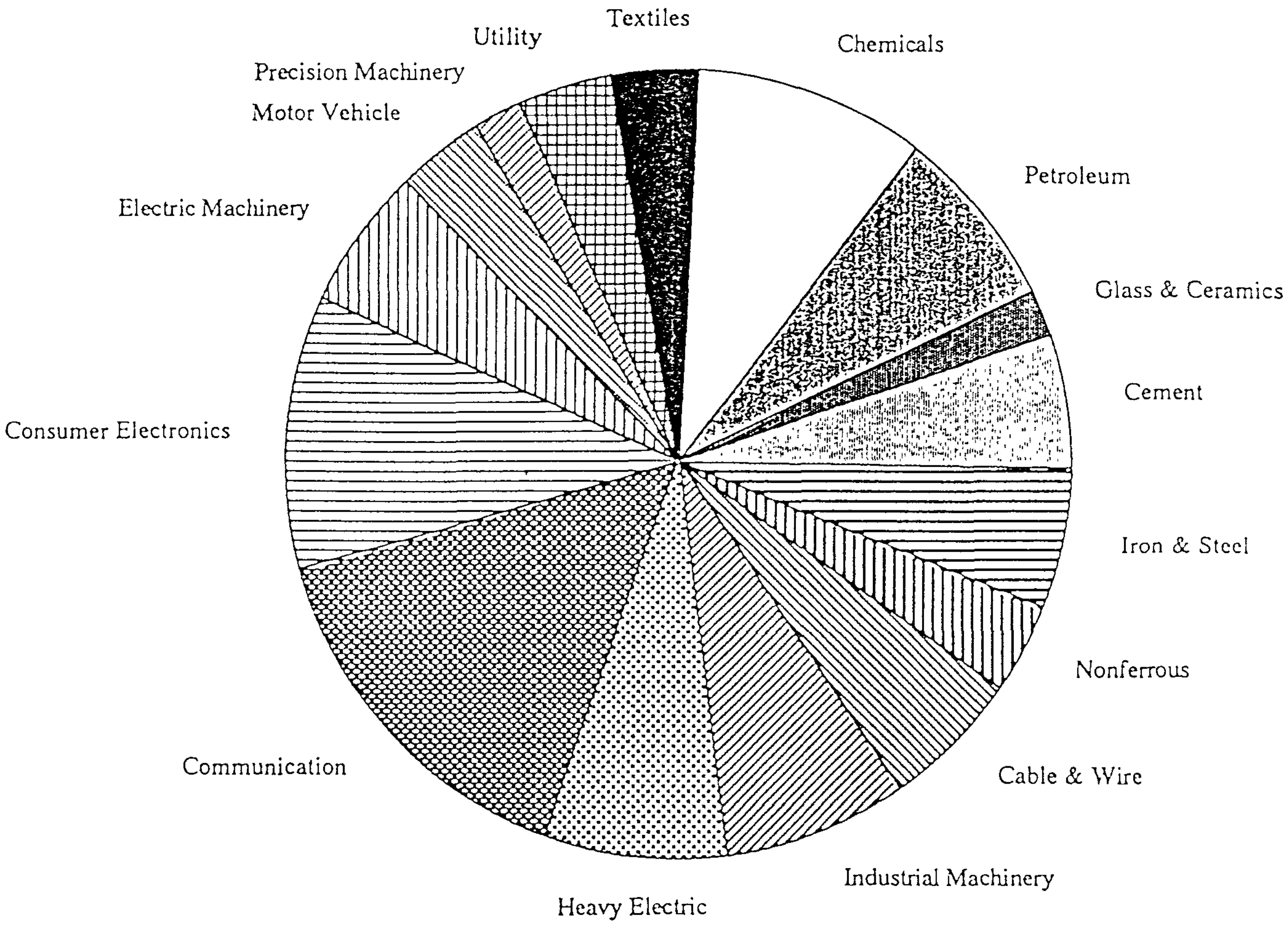


Figure 55. Industrial Sectors Cooperating in R&D with Universities - From Firms Identified in a Survey of 30 Universities



Contrary to popular image, the universities are seen to be an important partner for both new firms and established firms entering HTS. Although universities in Japan are frequently criticized for conducting research that is not of first rate quality and for being distant from the industry, the discovery of HTS shows that there are exceptions. It was a university which made the confirmation of the phenomena, and in a survey by the National Science Foundation in 1987, they found that universities were ranked among the top centers of HTS research, with the University of Tokyo topping all institutions, including firms. In new fields of science, universities have shown that they have an important role to play in educating the industry, and we can expect this type of interaction to increase as the number of university-industry linkages increases each year in Japan.

Regarding the influence of *keiretsu*, the evidence is that in superconductivity the tendency to collaborate within a *keiretsu* is quite strong. This is contrary to general industry data, which shows intra-*keiretsu* activity typically accounting for 25-50% of all joint patents.[166] This difference, however, reflects a different industrial structure in superconductivity. As the LTS industry is a small one and as relationships had been well established, there was virtually no migration across the industrial groupings. This may change should the HTS industry grow and broaden, but in the initial period of HTS growth we saw that most collaborations were with universities and public institutions.

Finally, regarding the notion that there is a spin-off from government programs through the creation of new relationships in innovation, there was no evidence of this in the patent application data.

Overall the analysis tells us to be careful about sweeping generalizations of collaboration in Japan. Collaboration patterns will be strongly influenced by the size of the markets and the structure of the industry. The narrow markets and established relationships in the traditional superconductivity industry have resulted in the patterns observed here. If there is an underlying principle, it appears to be one of practicality in innovation. The industry evolves to practical relationships which strengthens the market position of the firms, and while giving priority to these relationships in innovation, where experience is inadequate, the industry turns to universities and public bodies in search of training and new ideas.

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[166] Kikai Shinko Kyokai Keizai Kenkyujo, op.cit., p.22.

## IX. CONCLUSIONS

In examining the development of superconductivity in Japan and the role of research consortia, three issues were of primary concern: 1) How were these programs formed - who has the lead? 2) How are these programs organized and executed - what's the role of cooperation and of competition? 3) What impact do these programs have - how do the programs advance the science or the technology?

The formation of the project was used to test theories about where the lead lies in government supported research programs. Here a commonly held view, particularly with regard to high temperature superconductivity,[167] is that MITI consciously takes the lead by setting forth a research agenda around which the private sector will rally, consistent with the theory that the government acts as a strong "plan-rational" state.[168] This is not an image which applies to superconductivity.

Rather, it is the companies, the national laboratories, and university professors that take the lead in considering and recommending areas of government support. The industrial associations, in particular, are seen to be important centers of research proposals as well as vehicles to gain legitimacy in the private sector for the promotion of the technology or technology area.

MITI is integrated into discussions in the early stages and its direct influence depends on the clarity of the technological goals, which in turn vary with the degree of advance of the technology, the range of technical options, and the technical uncertainty. The more narrow the range of promising technical choice, the more directly MITI can exert an influence in the early stages. An important aspect influencing MITI's interest is the extent of advance overseas. If the work is of substantial interest at prestigious institutions overseas, it has generally been of interest at MITI.

As research has increasingly pressed the frontier and as the uncertainty and range of options has consequently increased, MITI has had to increasingly rely on outside sources to propose and evaluate ideas. This trend of drawing on an extended network to initiate projects is likely to continue in superconductivity and other fields as capabilities in Japan continue to advance.

Where MITI does contribute more substantively is in forging support in the government and industry necessary to sustain the project for the length of its multi-year

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[167] See earlier references to R. Inman, Japan Technology Evaluation Center and M . Crow.

[168] The "plan rational" state refers to a theory in political science developed by Chalmers Johnson to describe the strong influence of the bureaucracy over the direction of the economy and the state.

plan. For organizations directly regulated by MITI, such as the utilities, the coercive powers for participation are significant. Even for firms without a lot to gain from participation, MITI's call can still be persuasive because of the many regulatory powers that it still holds. In addition, MITI officials spend much of their time negotiating within MITI and with the Ministry of Finance for annual appropriations. MITI may not motivate the ideas, but MITI makes the ideas happen.

With the discovery of HTS, we see the same general conclusions apply to formation, as this type of breakthrough in science does not draw the political attention needed to circumvent the normal budget process. The discovery of HTS was not a "politically" significant event in the eyes of most members of the national Diet so the HTS programs in MITI and the STA had to abide by the normal budgetary schedule and thus had to wait a year and a half before funding was authorized. MITI did not, and in a budgetary sense could not, move at the speed of light.

In the language of political science, the mode of the government in the creation of these national technology projects was one of "technology -determined reciprocal consent,"[169] with the reciprocity being absent of an active role by the Diet, and with the balance determined by the clarity of the technical targets.

In examining the organization and management of the government programs, the role of cooperation was of primarily interest. Was it achieved? How? What form did it take? One hypothesis tested was that cooperation was achieved through the targeting of precompetitive, technology-base research. A second hypothesis tested was that there is some unique form or level of collaboration that occurs in Japan as a result of its culture, tradition, or institutions.

The cases revealed that the notion of precompetitive cooperation is an alluring but deceptive one which does not usefully describe any of the LTS cases. It is the perception of the *appropriation* that most influences behavior, not a willingness to be cooperative in precompetition. The cases revealed that when collaboration was achieved , it was not in a way which would be unexpected of firms acting rationally, and was realized in a way achievable by firms in the United States.

In the LTS cases, using superconductivity rather than developing superconducting materials was typical before the discovery of HTS. The development of the superconducting material itself was never a major part of any of the LTS activities. Working with the superconducting wires to provide the desired magnetic functions was

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[169] "Reciprocal Consent" refers to a theory in political science developed by Richard Samuels which models the policymaking process in Japan as a highly interactive one between the leaders of industry and the government, with the lead varying depending upon the issue.

often a challenge, but much more an engineering one than one involving scientific discovery. This work was certainly not precompetitive.

Second, we saw that more than leap into the future, the majority of the projects until recently were designed to emulate work initiated abroad with most formal technical goals incremental rather than revolutionary. In many cases, the goals were not beyond the world standard at project outset, but something close to current world performance. That is, it was largely known that the performance goals can be achieved at the start of the project. If the technical goals are modest, the programs are likely to be "technically successful." This reflects the "*tatemae*" of the process, with the stated goals often not being the true focus of the activity.

Regarding the behavior of the firms, it was seen that the firms acted in a manner consistent with a rational actor assumption of organizational behavior. Evidence of a "cultural" influence which manifests itself in unexpected collaboration between competing firms is not evidenced. Instead the firms behave largely as we would expect competing firms to behave, appropriating technology when possible. It is a recognition of these interests in the design of the program that creates value, competitive and cooperative, for the consortia. Japan's research consortia are not culture-bound, as Japanese firms give priority to their competitive interests just as American firms do.

Some level of cooperation was seen when knowledge about what can be appropriated from participation was still low, or when there was a technological imperative and a third party was acting to catalyze the activity. The greatest amount of cooperation between competitors occurs in the years preceding the start of a typical project. This is a learning period when firms are pooling resources to study what the state-of-the-art is, and to do some preliminary testing of the technologies. The certainty about what can profitably be appropriated is low and the benefit of learning from the common activity is high. Here cooperation occurs.

Early in the project firms still describe some exchange of information about evaluation techniques and about equipment to be purchased for experiment. But as the projects progress, the firms are better able to judge what they would like to withhold and programmatic collaboration turns more toward competition.

As a result, in device projects, as each of the firms develops the skills to pursue the technologies in-house, the technologies are increasingly developed separately and competitively. Similarly in systems projects, the principal systems developers still expect to be competitors in the marketplace and were similarly seen to guard their interests.

In the case of science, we see that collaboration can occur when the organization demands it and appropriation is sufficiently uncertain, but will not occur spontaneously if the firms are allowed some measure of insulation. In the ISTEC program, we saw that Prof. Tanaka and MITI seem to have achieved a thorough mixing of individuals from the participating firms in each of his six divisions. Participation appears to reflect the skills of the individuals and their geographic preferences more than reflect segregation due to the proprietary interests of the firms. In the Multi-Core Program, by contrast, the firms are allowed to send researchers to research centers or user facilities to conduct specific tasks. While the nature of the work is fundamental, the work is more formally insulated.

It has been postulated that although the firms conduct their research separately rather than jointly, frequent forced meetings create a "culture of exchange" of information between members of the firms.[170] This, however, seems to give an exaggerated perception. In interviews with both participants and advisors, while there is an admission the interactions are easier between the same individuals as years pass, most place little value on the bulk of the information exchanged. Over time there is more competition than cooperation.

The meetings do, however, provide the important competitive function of allowing the competing members or teams to keep track of the technical advance of its rivals and possible improve their own position. In interviews, participants generally discounted the technical value of the information exchange between teams, and instead emphasized intra-team exchange and the sense of competition that existed in the projects. This mutual ratcheting-up through competition is a key dynamic of the projects.

Key to the design of the programs is the nurturing of this competition more than trying to force cooperation. In virtually all cases of systems or device development, more than one firm, typically three, are selected as primary developers and work in parallel on the key aspects of the project. The plan is not to select a "national champion" which will monopolize the domestic market, but a set of strong firms which would be internationally competitive.

Competition is used during the operation of the consortia to enhance development. When there is clear cooperation it was often in competitive teams, typically in systems projects. Here organizational cooperation occurred when the interests of the firms were vertically matched in supplier-user relationships. They were thus coordinated in a manner which was consistent with their competitive interests.

Further, competition by these same players is desired upon completion of the project to get the technology into the market. Thus competition is leveraged to speed

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[170] National Research Council, R&D Consortia and U.S.-Japan Collaboration, Report of a Workshop, Washington: National Academy Press, 1991, p.20.

development during the project and competition can be relied on to accelerate the advance of the technologies toward the market.

Consortia fostering competition is much more important than consortia for cooperation. It is this ability to exploit competition and coordinate non-competitive links, or *"procompetitive coordination"* which is a trademark of the consortia.

If we model the relationships between firms in a simple interdependent decision matrix, we find a situation resembling that in Figure 56 between the major system and device developers. Instead of seeing substantial cooperation, we see substantial competition, with ISTEC and part of the linear motor car program being the only exceptions. In the case of ISTEC, the characteristics of the science, the persuasiveness of MITI, and the influence of the Laboratory Director induced a cooperative outcome, and in the case of the linear motor car it was the physical demand of one piece of infrastructure.

| | | FIRM B | |
|---|---|---|---|
| | | COMPETE | COOPERATE |
| FIRM A | COMPETE | Josephson Jct.<br>HTS Devices<br>Parametron<br>Super GM<br>SC Sensor<br>Multi-Core<br>Linear Motor Car<br>(Systems Devel.) | |
| | COOPERATE | | ISTEC<br>Linear Motor Car<br>(Cable Mfgs.) |

Figure 56 Interdependent Decision Matrix Representation Relationships Between Principal Firms

In the case of all other programs, the firms exhibited competitive solutions.

This pattern reflecting strongly competitive behavior was also witnessed in the industry generally. When cooperative patent applications in superconductivity were examined over the last 20 years, we saw no evidence of collaboration between competitors except in cases where the government or the utilities were also involved to force the collaboration. Collaborations between firms were not only largely vertical, but for the larger firms, were primarily within their industrial grouping. Competitive appropriation again underlies the cooperative behavior of the firm.

Although bureaucratic rivalries appear to be at least as intense as firm rivalries, with little cross participation between bureaucracies and their national laboratories, there seems to be little negative effect on the firms and the universities, with these organizations perhaps benefiting from the insulatory behavior. Even though the bureaucracies do not cooperate, the principal firm beneficiaries of the projects are generally the same. After establishing their administrative domains in transportation, or energy, or sensing, the different programs in the different bureaucracies end up funding the same set of firms to do the work. This is particularly true for LTS projects.

University professors also seem to benefit from the division of bureaucracies as they can move across borders to gain from the different resources offered. From their own ministry, the Ministry of Education, they receive research grants; from the Science and Technology Agency they can get free access to state-of-the-art research equipment; and from MITI they can develop their industry connections and receive some level of remuneration for participation on advisory committees. Bureaucratic rivalries do not appear to have handicapped superconductivity research at the bench level.

The third general issue is one of impact. With the formal goals as *tatemae*, the *honne* lies in impact on a variety of dimensions of innovation, with differences seen to arise between projects targeted at devices vs. systems vs. science. Table 27 summarized the differences discussed in this chapter and their relative importance to the different categories of technologies. The results are again generally consistent with the outcome expected of competitive, rational actors in a collective activity, where uncertainty and appropriability strongly influence the value of the various benefits. Some of the more notable points include the following:

- The relative importance of the government program to the firm in the specific technology area is typically high, often accounting for more than 50% of the firm's effort.
- The progress made in the core science and technology in past LTS projects is typically incremental, not revolutionary, although the leap is increasing.

Table 27 Summary of Differences between Systems, Device, and Science Projects in Collaborative R&D in Superconductivity

| | Systems | Device | Science |
|---|---|---|---|
| Examples | Super GM<br>Superconducting Sensor | Josephson Jct<br>HTS - ED<br>QFP | ISTEC<br>Multi-Core |
| Formation | User/ Association | Gov't Lab/ Industry | Scientists/ Gov't Lab |
| Organizational Mode | Coordinated and Competitive | Insulated and Competitive | Mixed - Varying on Ability to Appropriate |
| Benefits | | | |
| *Importance Relative to In-House Firm Activity* | Significant | Moderate | Small to Large |
| *Core Science and Technology* | Incremental<br>Eqpt. Purchase | Incremental<br>Eqpt. Purchase | Incremental to Advanced Technology Base-<br>Eqpt. Purchase |
| *Diversification* | Small | None | Moderate |
| *Diffusion* | Small | Small | Moderate to High |
| *Complementary Assets* | Peripherals<br>Users | Unclear | Research Eqpt<br>Processing Eqpt |
| *Training* | Moderate | Moderate | Significant |
| *Enabling Competitors* | Significant | Significant | Significant |
| *Sustaining a Technological Base* | Significant | Significant | Significant |

- A major direct benefit to both to the national laboratories and the firms is the acquisition of expensive R&D equipment. As most of the budgets received by the firms, and all of the budgets received by the national laboratories are spent on equipment and materials, participation allows for a significant upgrade with state-of-the-art equipment.
- A less direct but equally important benefit is the acquisition of markets and nurturing future markets for superconducting products. Government R&D and laboratory projects have been the principal markets for superconducting wire and magnets for the length of the industry's history in Japan. In the case of the superconducting generator program, the linear motor car, and the MHD generator program, the market is well defined.

Participation in the the government development programs would be an important entree to the eventual markets, with the accumulated experience effectively serving as a barrier of entry to other firms. Note that in the programs, the principal firms are always the same.

- Ferreting out "blind alleys." The incremental design of the programs and style of research are well matched to the function of exploring a variety of paths and ferreting out unproductive approaches. This appears particularly true of the research in HTS.
- Establishing common evaluation techniques. For research to advance it is important for the language of progress to be common. An emphasis on evaluation at the beginning of the program provides for a common technical language and for a sense of which evaluation techniques are most effective and reliable.
- The science projects contribute to both diversification and diffusion but the technology projects strongly favor major, established actors.
- Developing complementary assets is a designed benefit in systems projects, and a more serendipitous result of progress in science. For superconducting systems this meant developing the supporting refrigeration, shielding, control, or sensing technologies needed to realize full development, and developing new research and processing equipment to enable the advance of a new field.
- Training is a particularly important benefit of the science projects, although it clearly benefits all projects to some extent. For the HTS projects, training appears to be the principal anticipated benefit of the firms, a benefit more difficult to achieve in the United States because of greater job mobility.
- Common to all projects is the benefit from increasing the technological level of competitive firms or teams which will take the developments into the market. A priority on the commercial capability of the participants and the leveraging of procompetitive coordination results in a level of increased industrial capability that is at least closer to the state-of-the-art, if not defining the frontier.
- Also common to all projects is the value contributed through long-term support of the technologies, which aids the maintenance of a technological base. In many of the LTS cases studied, it is the length of commitment and the time provided for incremental improvements where the government provides its most important contribution. The MHD project was initially scheduled to run for 5 years, but development was found to be more difficult than expected. As the utilities, a semi-public set of bodies, would be the primary beneficiaries of its success, the market was narrow and development would not be expected to continue without public support. The project was thus continued for an additional 12 years.

Development of the linear motor car began in 1970 and continued improvement of the superconducting magnets and prototype testing is continuing today, 21 years later. The first superconducting electricity generator project was initiated in 1974, the next in 1977 and the next in 1988, with a final prototype project anticipated to begin in 1996. Thus 22 years will have elapsed between initial government support and the start of the development of a practical prototype.

Even in the case of the Josephson junction, which was targeted for a more general commercial market, the ten year length of the government program allowed the firms to continue the effort for 7 years after IBM dropped out and helped them attain a clear international lead in this technology.

The same is true of the HTS projects. The MITI program assures that there will be a sustained, 10-year effort, to advance the performance of these materials with a laboratory of about 90 researchers. The STA program will allow the STA laboratories to acquire state-of-the-art, and sometimes internationally leading research facilities for HTS and other materials research which will continue to be available once the formal 5-year term of the program expires. The program will at a minimum provide for a much enhanced ability to conduct science over a period far outlasting the program.

In this history an analogy can be drawn with the development of the computer industry in Japan. Over the 25 years of government support for R&D consortia in computer-related areas, many projects in hardware and software were created. When viewed individually, most failed to achieve the kind of market impact that was hoped. But when viewed collectively, we can see a long-term, sustained history of support the industry until it is today, among the strongest in the world.

As the scientific activity of the consortia alone has been seen not to be a principal goal of most of the superconductivity cases, policymakers elsewhere in the world should bear this in mind when developing programs ostensibly modeled on the "Japanese experience." Simply establishing 4 to 6 superconductivity consortia involving universities, national laboratories and the industry, as recommended by The Committee to Advise the President on High Temperature Superconductivity,[171] may only provide marginal scientific or commercial returns.

Superconductivity has been raised in an environment of "bounded competition" in Japan and has been an industry which has required long-term support. Whether or not one accepts the argument of the Council on Superconductivity for American Competitiveness

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[171] High Temperature Superconductivity: Perseverance and Cooperation on the Road to Commercialization, Washington: The Committee to Advise the President on High Temperature Superconductivity, 1987.

that the U.S. government needs a 5-year, $250 million dollar program,[172] policymakers should be aware that this is a technology which needs sustained commitment.

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[172] David Stipp, "Superconductor Group Recommends Joint Industry-Government Program," Asian Wall Street Journal, June 18, 1991.

# APPENDICIES

## APPENDIX A. Superconducting Magnets Used at the National Laboratory for High-Energy Physics (Superconducting Mangets and Cryogenic Systems in KEK, Monbusho, Ko-Energi Butsurigaku Kenkyujo, April 1991)

| Magnet Name | Year | Field strength (B-max, T) | Current (A) | Stored Energy | Manufacturer |
|---|---|---|---|---|---|
| Septum Magnet | 1981 | 2.1 | 2240 | 52 kJ | Furukawa Electric |
| Benkei - Large Aperture | 1982 | 3.5 | 610 | 3.15 MJ | Mitsubishi Electric |
| SD 430 | 1982 | 4 | 3518 | 615 kJ | Furukawa Electric |
| TOPAZ Solenoid | 1984 | 1.3 | 3650 | 19 MJ | Furukawa Electric |
| VENUS Solenoid | 1986 | 0.75 | 4000 | 11.7 MJ | Mitsubishi Electric |
| AMY Solenoid | 1986 | 4 | 5000 | 40 MJ | Hitachi Ltd. |
| 10 Tesla Dipole | 1985 | 10.4 | 6340 | 728 kJ | Hitachi Ltd. |
| 14T Split Solenoid | 1989 | 15.1 | 570 | 1019 kJ | Mitsubishi Electric |
| 5 Pole Vertical Wiggler | 1989 | 6.9 | 220 | 220 | IHI Co., Ltd. |
| PCMAG/BESS | 1990 | 2.2 | 512 | 815 kJ | Toshiba |
| Toroidal Magnet | 1990 | 1.85 | 1550 | 2.9 MJ | Mitsubishi Electric |
| Dipole, Hadron Collider | 1990 | 7.11 | 5968 | 50 kJ | KEK |
| Dipole, Hadron Collider | 1990 | 6.84 | 6500 | 50 kJ | KEK |
| Insertion Quadrupole | 1990 | 6.0 | 3405 | 336 kJ | Hitachi Ltd. |
| SKS Spectrometer | 1990 | 4.5 | 498 | 11.2 MJ | Toshiba |
| ASTROMAG Test Coil | 1991 | 5.6 | 800 | 10 MJ | Toshiba |
| LHC Model Dipole | 1991 | 10.2 | 12720 | 670 kJ/pair | Toshiba |

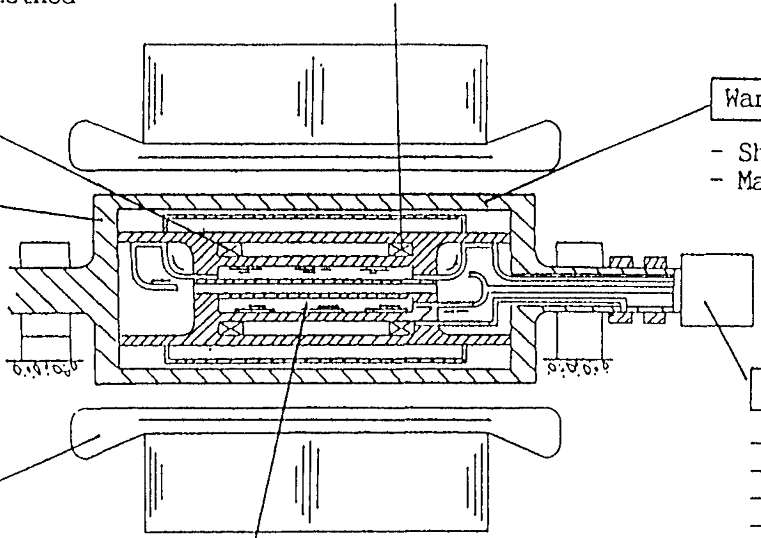
## APPENDIX B. Equipment and Facilities Advertised for Cooperative Research Use at the Mutli-Core Program Research Cores

| Core | Equipment and Facilities |
|---|---|
| Theory | Simulation management equipment |
| Data Base | Alloy design work station |
| | Data use system terminal work stations |
| New Superconducting Materials | Solid phase reaction methods |
| | Dry process method |
| | Multistage moisture method |
| | Sol Gel process |
| | Liquid phase reaction methods |
| | Ultra-fast quenching method |
| | Vapor phase reaction methods |
| | Surface modification method |
| | Solid pressurization methods |
| | High pressure solid phase reaction |
| | High pressure, multistage pressurization |
| | Sealed tube pressurization |
| | Vapor pressurization methods |
| | High pressure gas pressurization |
| | Other equipment |
| | 30,000 ton high pressure press |
| | Thick film ultra-fast quenching equipment |
| | High/low temperature X-ray diffraction meter |
| | SIMS |
| | SQUID magnetic field measuring equipment |
| Material Composition | Solid phase electrolysis equipment |
| | Light beam crystal growth equipment |
| | Light excitation reaction equipment |
| Thin Film | Multi-element low temperature reactor |
| | Controlled structure film layering equipment |
| | Auger electron spectral diffraction analyzer |
| | Mossbauer effect measuring equipment |
| Single Crystal | Pick-up equipment |
| | Condensing float-zone process equipment |
| | Top seed equipment |
| | High temperature stage microscope |
| | Portrait management equipment |
| Lithography | Real time evaporation multi-target sputtering equipment |
| | Laser evaporation equipment |
| | Light decomposition CVD equipment |
| | Laser surface alteration equipment |
| | Molecular line epitaxy equipment |
| | Electron beam exposure equipment |
| | Dry etching equipment |
| | Lithography equipment |
| Basic Conductor | Solid phase reaction methods |
| | Sputter process |
| | Vacuum evaporation |

    - CVD process
- Liquid phase reaction methods
    - Electron beam irradiation process
    - Ultra-fast melt cooling process
- Vapor phase reaction methods
    - Powder complex field process
- Chemical reaction methods
    - Sol Gel process
    - Application processes
- Plasma jet methods

| | |
|---|---|
| High Field | 80 T long pulse magnet<br>40 T hybrid magnet<br>20 T large bore magnet<br>Ultra-minute magnet field measuring equipment |
| Crystal Structure | Ultra-high resolution electron microscope<br>Powder X-ray diffraction meter<br>ESCA<br>Crystal structure analyses programs<br>High resolution electron microscope portrait analysis program<br>Photoelectron spectacle analysis program |
| Chemical Composition | Rutherford back scattering (RBS) equipment<br>CAICISS<br>Scanning tunnel microscope<br>Muon spectral diffraction equipment |
| Radiation | Gamma-ray irradiation equipment<br>Electron line radiation equipment<br>Neutron irradiation equipment<br>Neutron spectral diffraction equipment<br>Ion irradiation equipment |
| Physical and Chemical | XPS/ESCA<br>X-ray diffraction<br>SIMS/IMA<br>SQUID<br>Auger electron spectroscopy<br>Scanning electron microscope<br>EDX |

# APPENDIX C. Program and Performance Information Regarding the Superconducting Electricity Generator



**Superconductor**

- Enhancement of current density
- Reduction of loss
- Enhancement of stability
- Enhancement of capacity
- Electric insulation method
- Evaluation technique

**Field winding**

- Winding manufacturing method
- Supporting and fixing method
- Cooling method in transient state
- Winding insulation method
- Evaluation method

**Multi-cylindrical rotor**

- Vibration characteristic
- Manufacturing and assembling technique
- Structural material manufacturing technique
- Structural integrity evaluation technique

**Warm damper**

- Shield characteristic
- Manufacturing technique

**Air gap armature winding**

- Winding support method
- Optimum double transposed conductor

**Helium Transfer coupling**

- Helium gas seal
- Vacuum seal
- Penetration heat inhibition
- Security of reliability

**Cooling system**

- Effective cooling for field winding
- Effective cooling for rotor
- Cooling for structural materials in transient state
- Cooling and insulation method for current lead

**Operation control**

- Start/stop operation method
- Turning operation method
- Automatic control method

**Protection & detection**

- Quench detecting method
- Measurement method
- Diagnostic technique for abnormal operation

**Maintenance**

- Maintenance items and frequency
- Repairing technique

Fig. 3 Main R&D subjects of superconducting generator

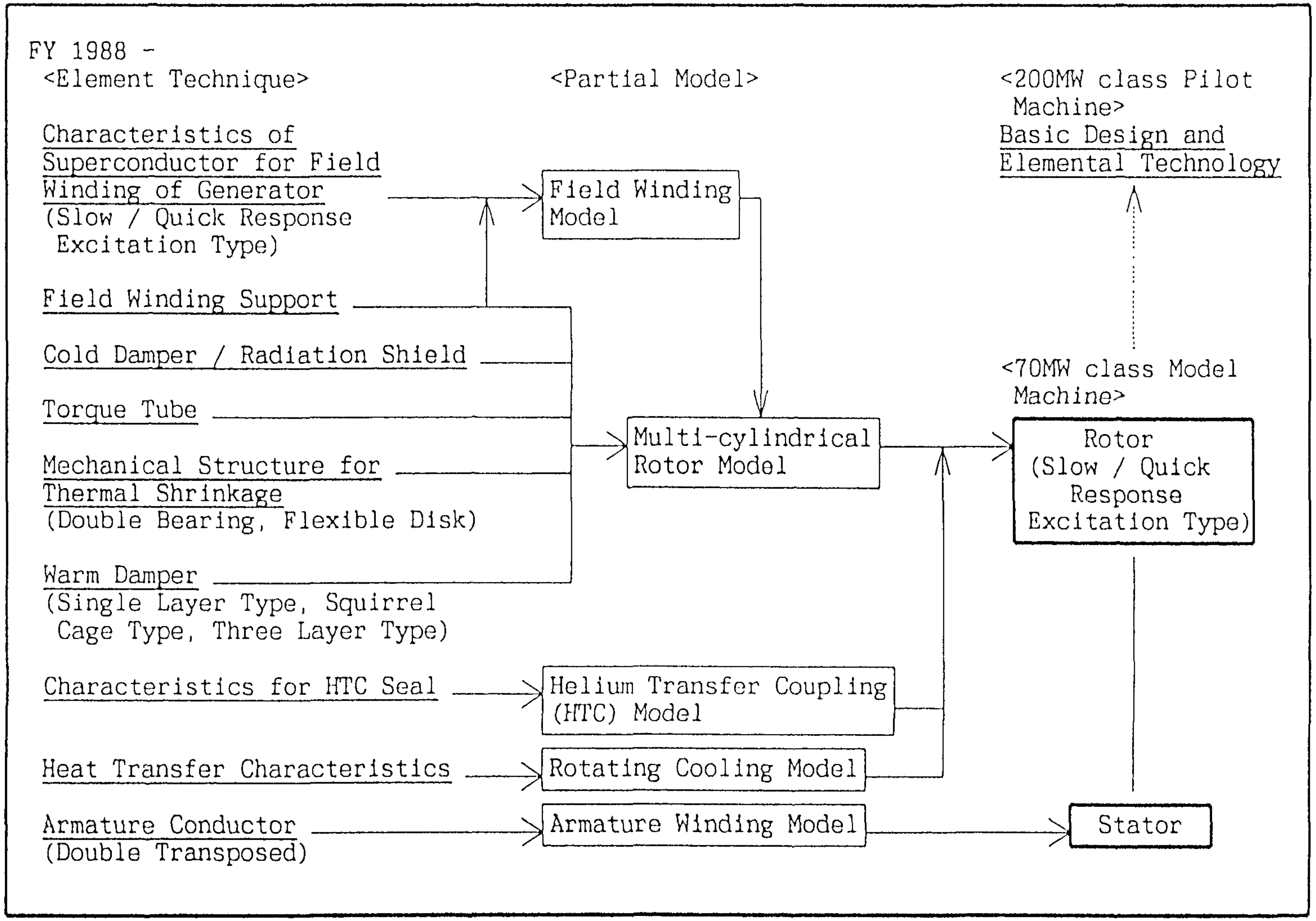
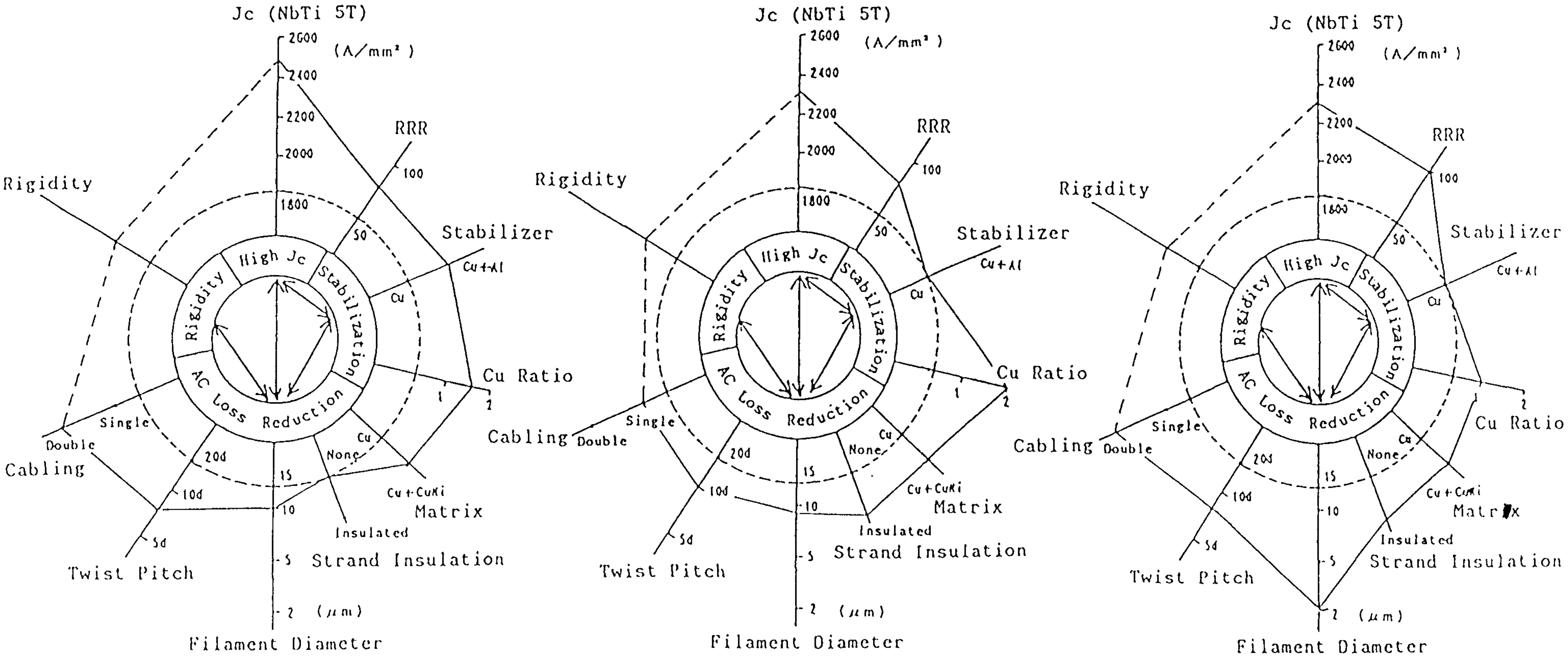


Fig. 4 R&D step for superconducting generator



(a) High stability type
(Slow response type A)

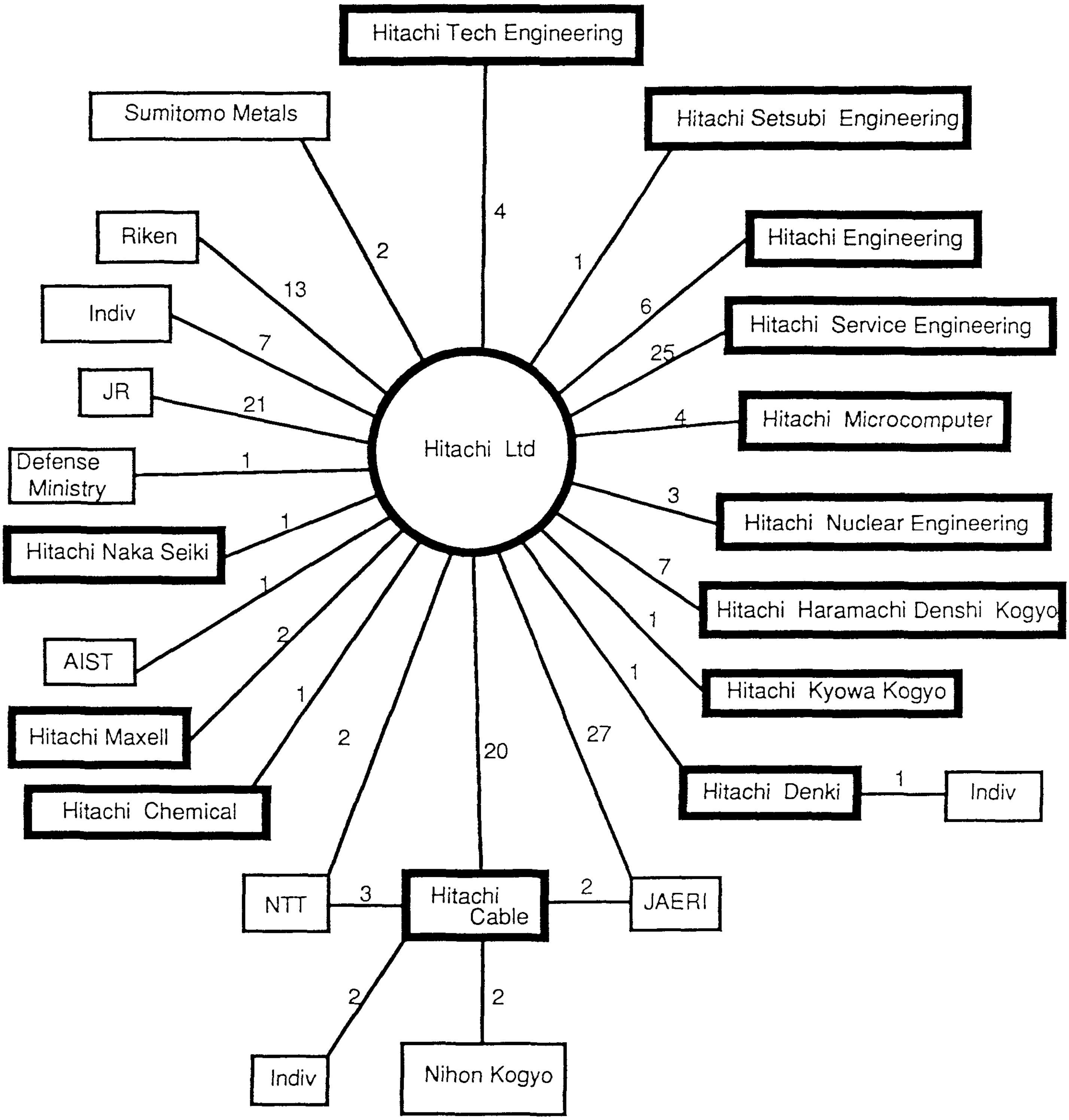
(b) High current density type
(Slow response type B)

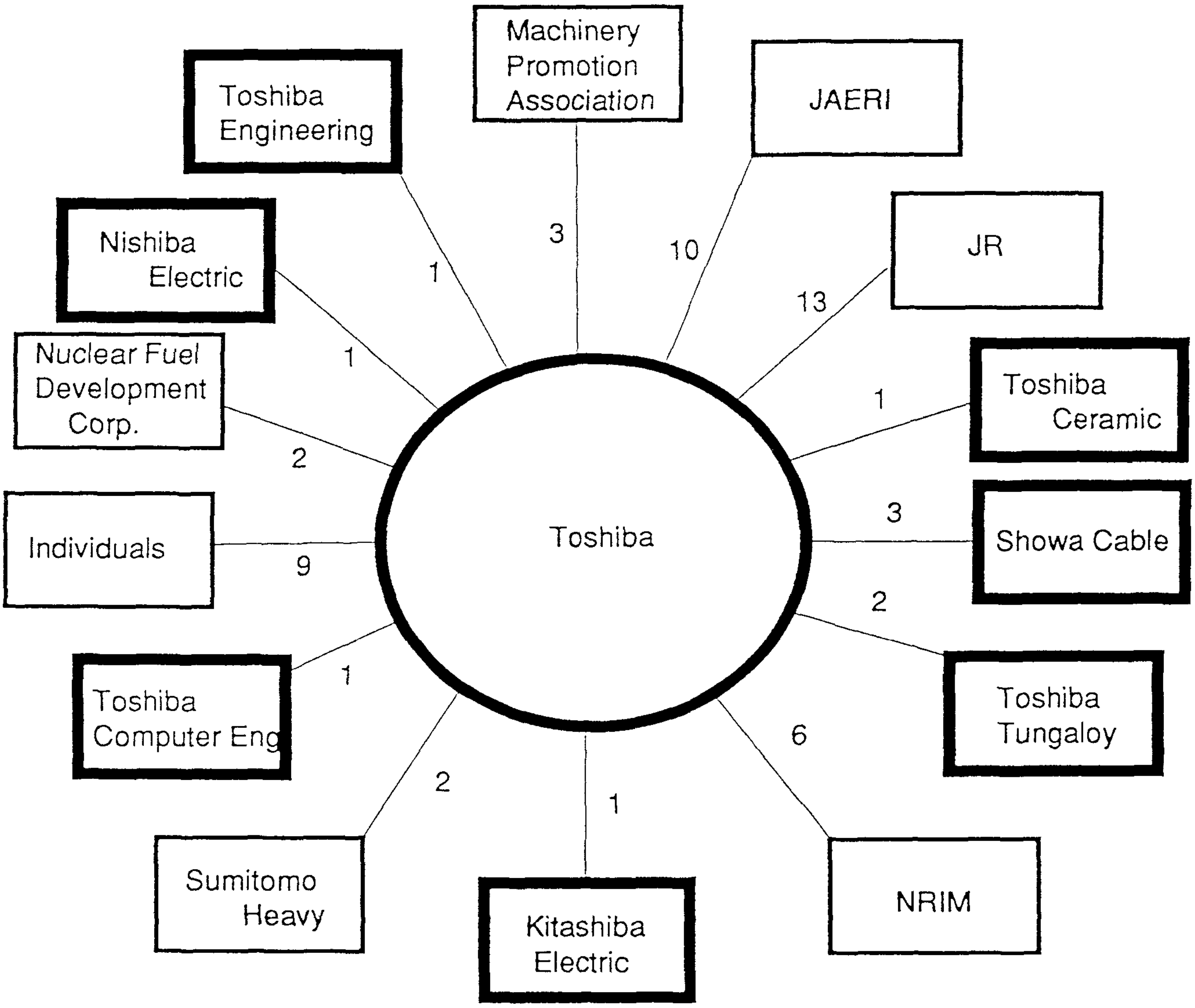
(c) Low AC loss type
(Quick response type)

Fig. 7 R&D target of NbTi superconductors

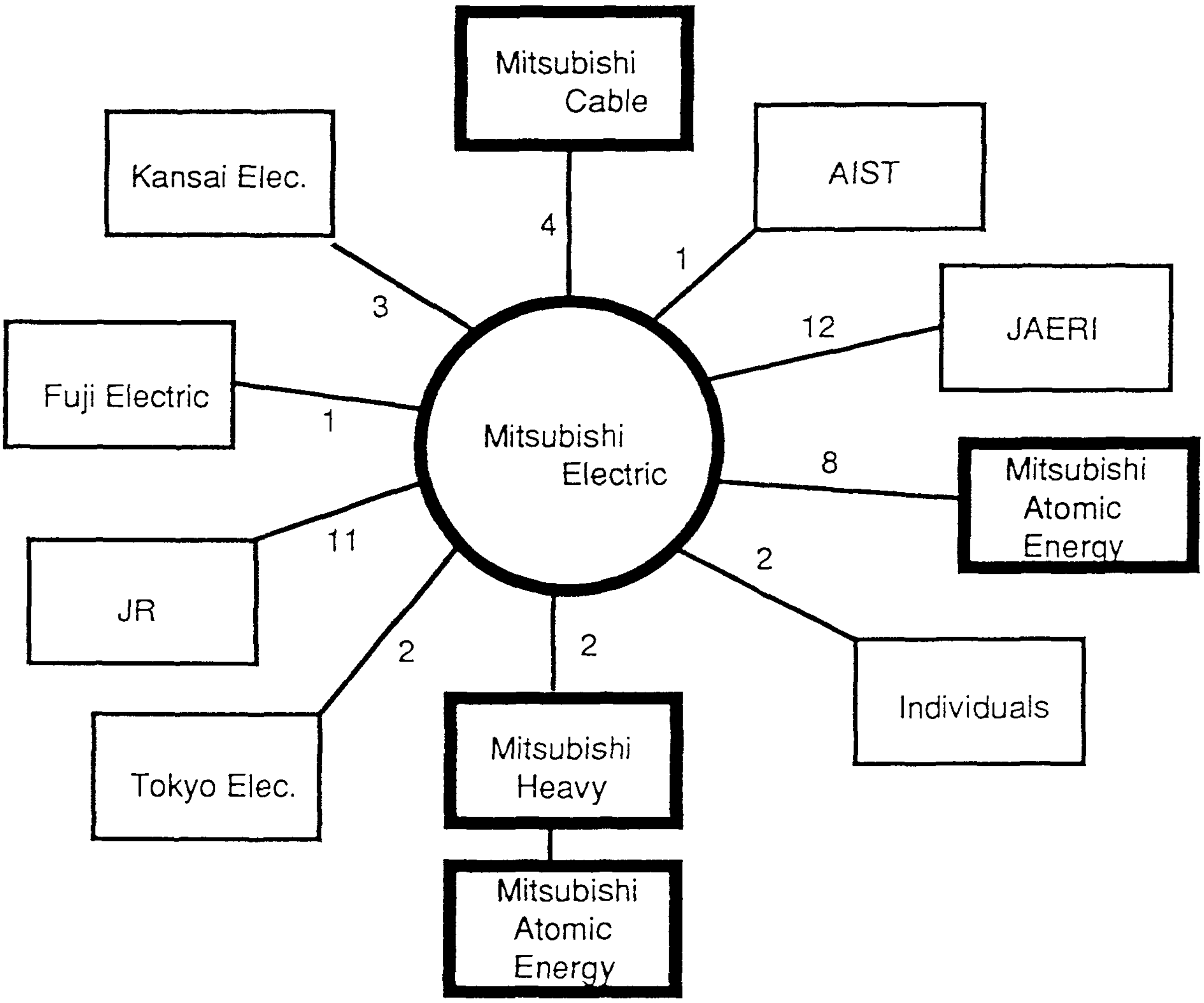
# APPENDIX D. Patent Application Collaborators with Major Systems and Cable and Wire Firms in Superconductivity

Cooperative Patent Applications in Superconductivity, Hitachi Ltd

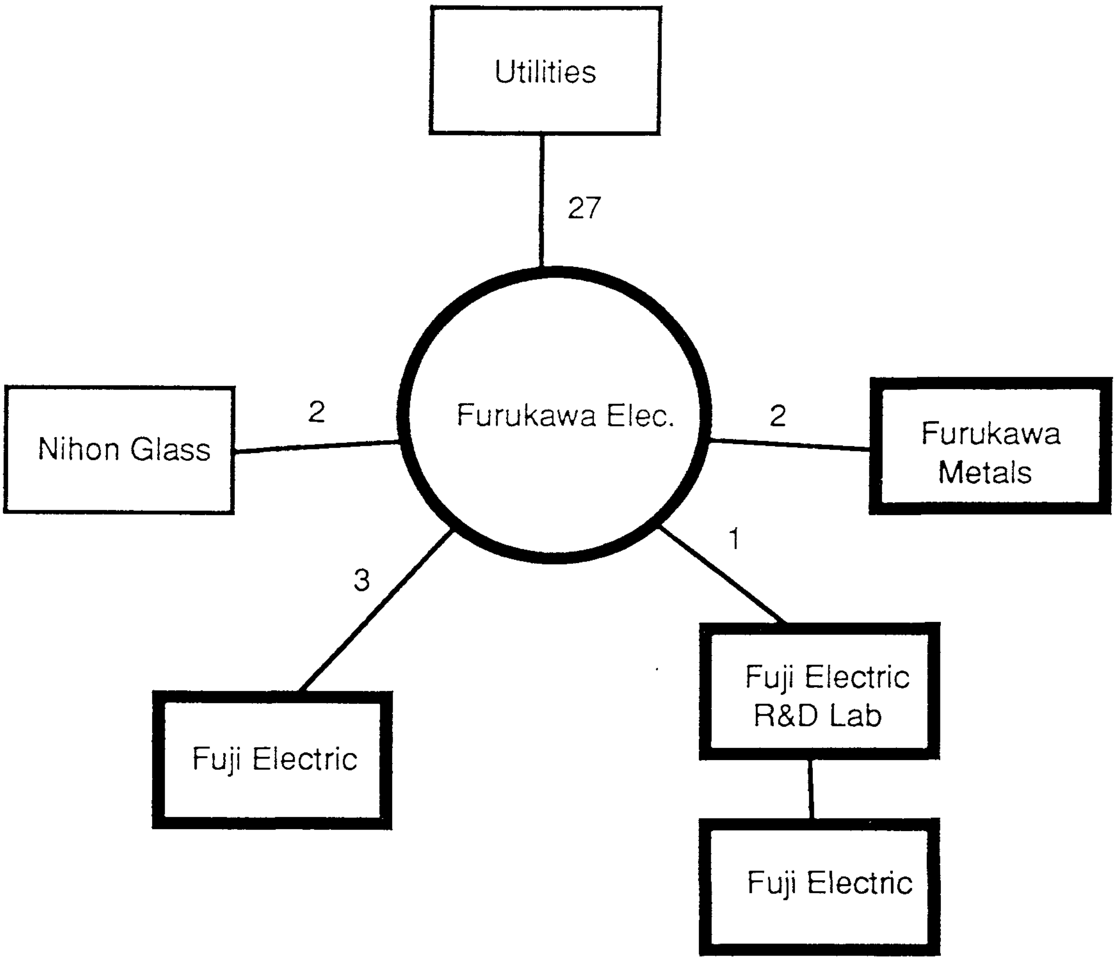




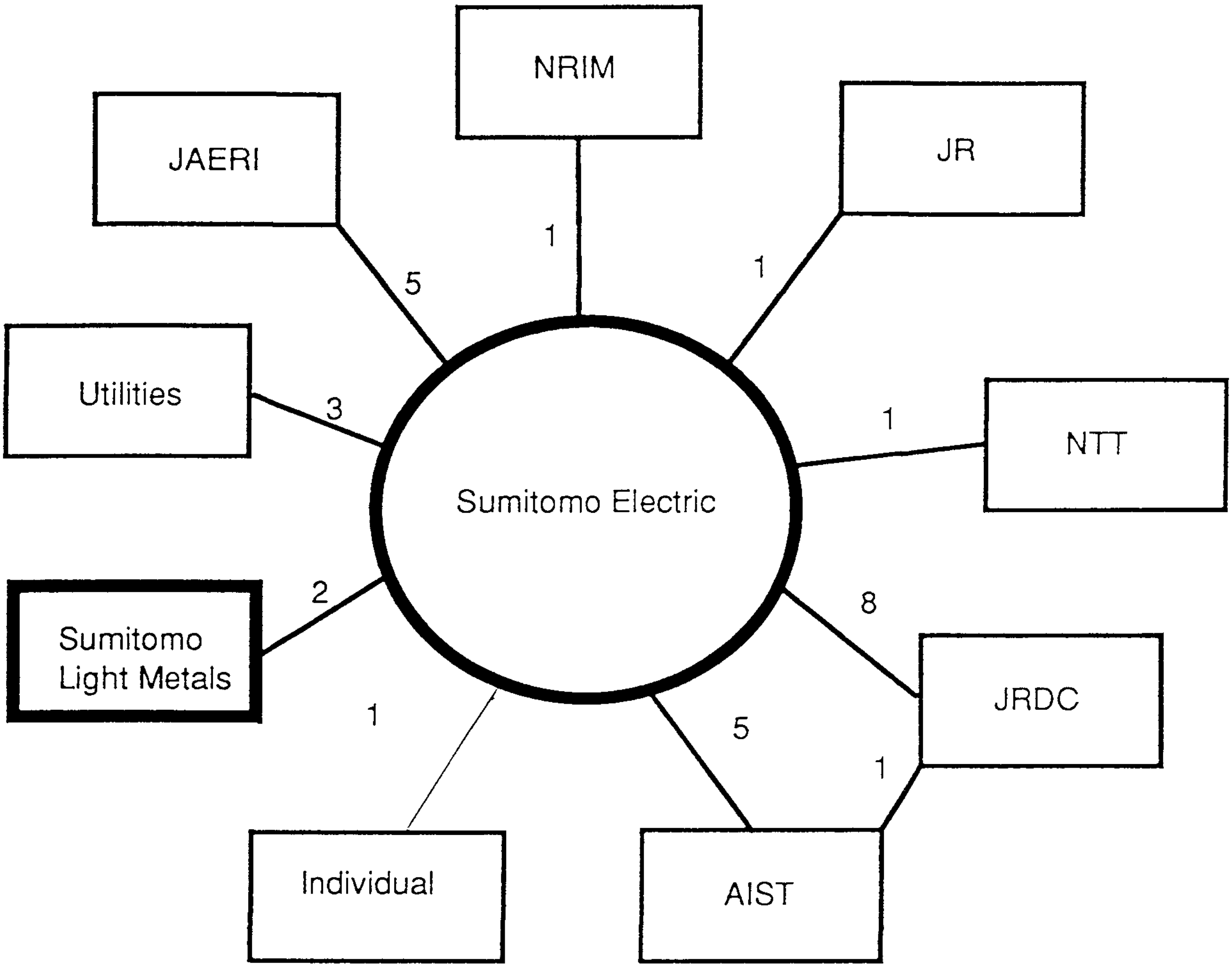
Cooperative Patent Applications in Superconductivity, Toshiba



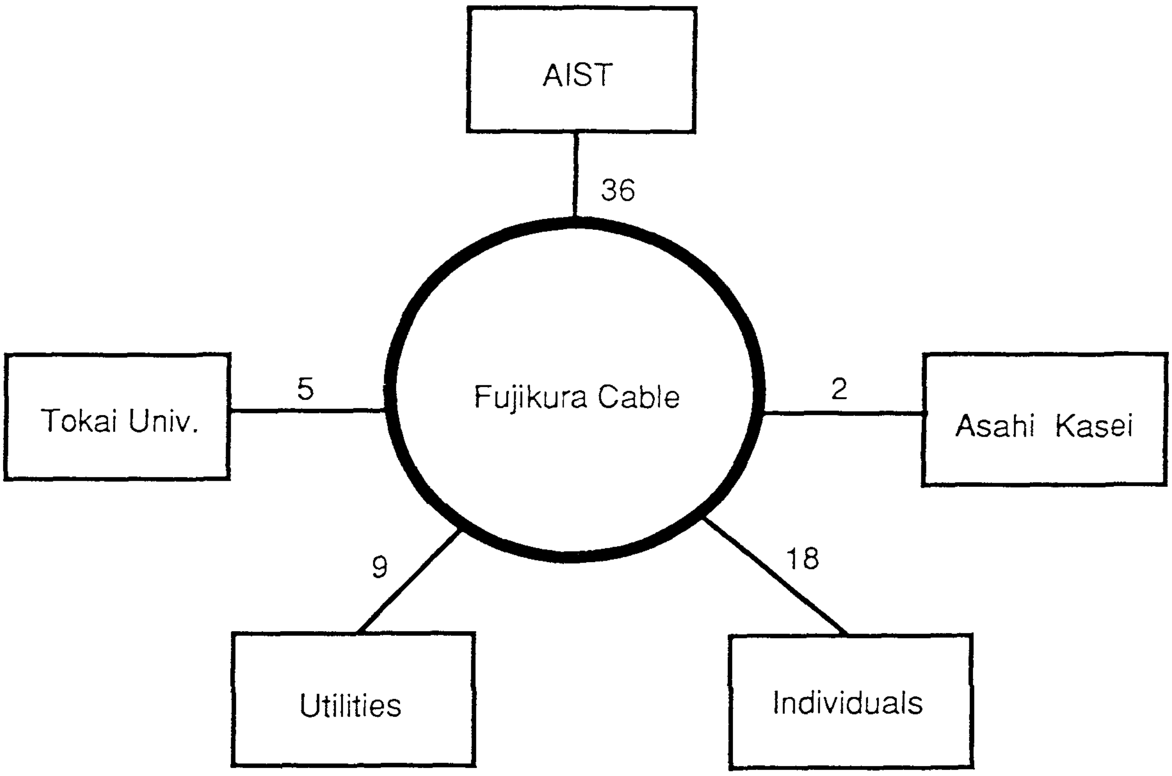
Cooperative Patent Applications in Superconductivity, Mitsubishi Electric



Cooperative Patent Applications in Superconductivity, Furukawa Elec.



Cooperative Patent Applications in Superconductivity, Sumitomo Electric



Cooperative Patent Applications in Superconductivity, Fujikura Cable