SUPERCONDUCTIVITY RESEARCH: A DIFFERENT VIEW

Will the US eventually lose the race to commercialize superconductivity? Or is the race already lost? Here is one person's perspective on the worldwide competition in high-T_c superconductivity.

John M. Rowell

Much has been written about superconductivity in the past 18 months. Some of it is technical, and usually it is accurate. Some of it promises applications on time scales that I find difficult to believe. But in a good fraction of this writing the technological challenge posed by the discovery of the new high-temperature superconductors is used to justify sweeping generalizations about US research, development and manufacturing capabilities. The theme underlying this sort of writing is that "superconductivity is our last chance to prove our technological prowess," or, more simply, "we will lose out to Japan—again." It is this aspect of the superconductivity news that I will discuss. I find that there is some underlying cause for concern but that many positive aspects of US commercialization of conventional, low-temperature superconductors are being ignored. Furthermore, suggestions that US industry is not contributing at the forefront of research in high-T_c superconductivity are demonstrably incorrect.

To some extent, I too have had some apprehensions about how well we in the US will meet the superconductivity challenge. Perhaps my thinking has been influenced by my owning Japanese cars, 35-mm and video cameras, VCRs, TVs and hi-fi equipment. I have even empathized with research colleagues when they expressed the feeling that "we will do the research, they will not pick it up, but Japan will run with it." Such a fear, I believe, runs deep in our research community, both in universities and in industry. On a closer examination, however, I find the fear is much exaggerated.

First, we are not doing all the research but only a fraction of it; in fact, research in the new superconductors is repeated and duplicated worldwide to such an extent that one wonders how essential and indispensable the contributions from any one country, including the US, really are.

Second, it is difficult to define "they"—who will not pick up the research for commercial applications in the US—in the above expression of the researchers' fear. Presumably it refers to some vague industrial body over which we as research scientists, even those of us in industry, have little influence. But as I will show, the

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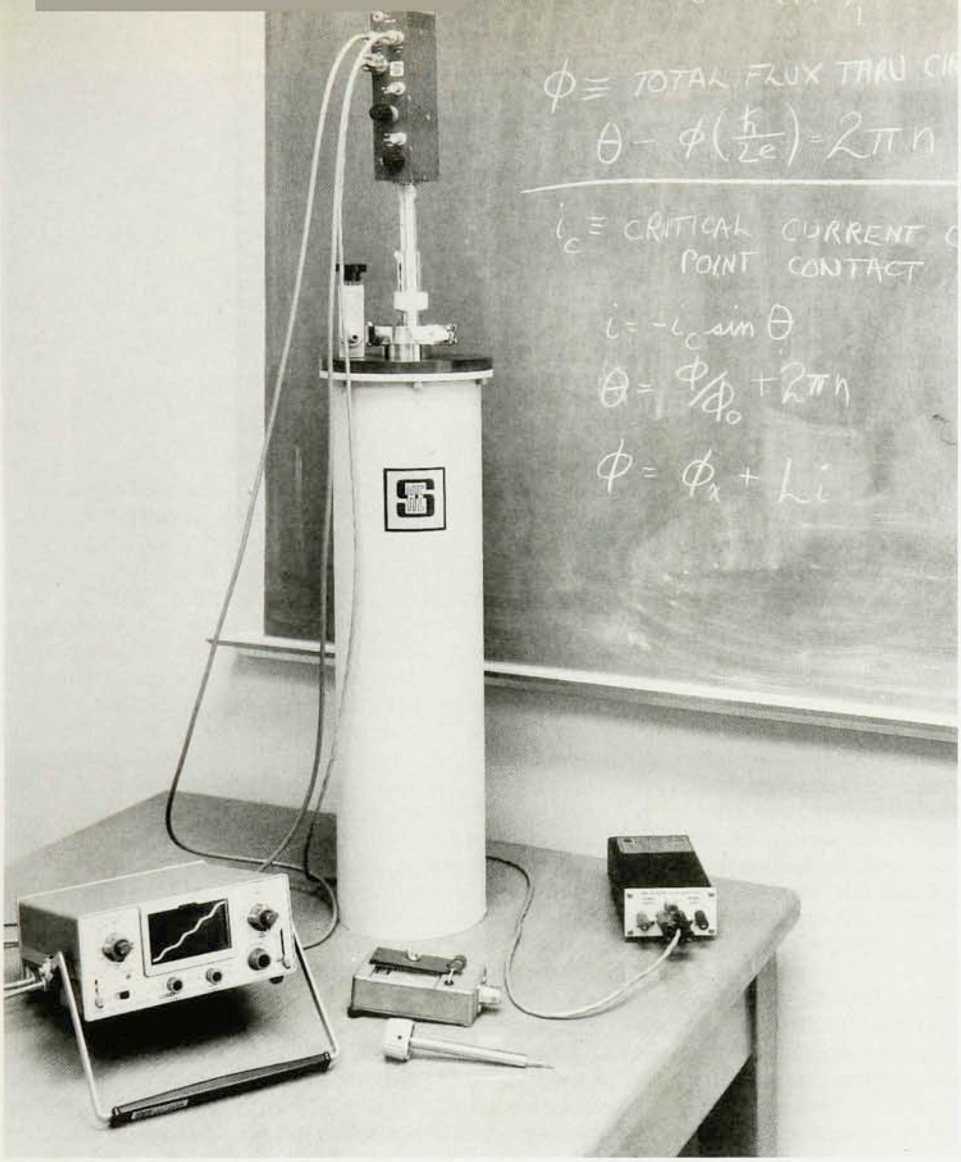


Superconducting magnetometer developed by the SHE Corporation of San Diego (now called Biomagnetic Technologies) in the early 1970s. The magnetometer is widely used in research laboratories for magnetic susceptibility measurements, and it has become a familiar instrument in the search for new high-T_c materials. (Courtesy Biomagnetic Technologies.)

commercialization of superconductivity in the past has generally been achieved by scientists themselves, and there is every indication that this will happen again.

Third, there is little evidence that any country is clearly in the lead in the race to develop large-scale commercial applications of high-T_c superconductivity. In fact I question whether such an international race exists. There is admittedly a healthy competition between groups to dominate, or even to contribute, at the research frontier, but my own view is that my colleagues at Bellcore feel the competition much more keenly with IBM and AT&T than they do, say, with Nippon Telephone and Telegraph or the University of Tokyo. I do not believe that research scientists in the US sense a need to mobilize to meet a foreign threat; the challenge they face comes first from nature, second from the large US laboratories, and then perhaps from our international colleagues.

Criticism of US industry

The criticism of US industry that we scientists previously enjoyed largely in private became a public denunciation in *The New York Times* on 27 March 1987. I present below some quotations from the *Times* article, entitled "If We Lose the Race, Blame Industry."

▷ "How is corporate America responding? By and large, with very tentative interest."

▷ "American industry in general is doing far less than the Japanese to commercialize this new technology."

▷ "Japanese corporations are reported to have filed more than 2000 superconductivity-related patent applications."

▷ "Japanese corporations are already boldly announcing new superconducting products."

▷ "The Japanese are taking to heart their own predictions that high-temperature superconductivity will turn into a $20 billion to $34 billion annual market by the year 2000."

▷ "Their main competition in the United States seems to be coming from an assortment of young companies that have sprung up over the last year or so."

▷ "The situation is the classic one that has troubled large-scale American industry since World War II. Major American corporations are inclined to emphasize short-term gains or savings over long-term research."

▷ "Major Japanese companies have been boldly announcing developments. It is almost as if they are thumbing their noses at American corporations and challenging them to match their progress. But American corporations remain eerily silent, either because they don't want to tie their hands or because they have nothing to announce."

▷ "Failure to develop a significant American presence in the emerging superconductivity industry deals a serious, perhaps crippling, economic blow to this nation. Our government is doing its share. This time American corporations have no one to blame but themselves. The

Discoveries of high-T_c superconductors

Material (T_c)	Discovery	Rapid follow-up
$(La,Ba)_2CuO_4$ (30 K)	IBM (Zurich)	U. Tokyo, U. Houston, AT&T, Bellcore
$YBa_2Cu_3O_7$ (90 K)	U. Alabama, U. Houston	Inst. Phys. Beijing, U. Tokyo, Bellcore–Natl. Res. Council Canada, AT&T, Argonne, IBM
Bi-(Ca,Sr)-Cu-O (85–106 K)	Natl. Res. Inst. Metals, Tsukuba	U. Houston, Bellcore–NRC Canada, Du Pont, AT&T, IBM
Tl-Ca-Ba-Cu-O (105–125 K)	U. Arkansas	IBM, Du Pont, Natl. Geophys. Lab., Johns Hopkins U., Sandia Natl. Labs.

window of opportunity is open; it will slam shut in a very short time."

The *Times* article, even though based on many grains of truth, seemed to me so extreme that I decided to reexamine my own prejudices about the malaise that I believed affected US industry. Being a scientist, I looked for data instead of basing my analysis on rumors. (My friends, who know how I spend my time these days, will, I hope, forgive the claim that I am still a scientist.) I confined myself to superconductivity, rather than to VLSI or optoelectronics, where my conclusions could well be different. I examined four aspects of research and development work in superconductivity: first, contributions to the high-T_c field; second, the formation of consortia; third, contributions to conferences before and after the discovery of the high-T_c materials; and fourth, the products based on superconductivity that are commercially available today and the creation of new superconductivity companies.

An extensive and thoughtful report from the Office of Technology Assessment in Washington, entitled "Commercializing High Temperature Superconductivity," appeared recently. The report's main conclusions are only slightly kinder to the US industry than is the article in *The New York Times*. Here, for example, are some of the conclusions:

▷ "American industry, by and large, looks for safe bets; few managers view research as a major element in long-term competitive strategy."

▷ "They [American companies] plan to take advantage of developments as they emerge from the laboratory—someone else's laboratory—or buy into emerging markets when the time is right."

▷ "Many larger American companies have pulled back from basic research and riskier technology development projects."

The report also dismissed research in US government laboratories, saying: "DOE's basic research, like that of DOD, will help support the technology base. As for commercial technology, the laboratories are trying to develop new cooperative ties with the US industry. However, it could take years for effective working relationships to develop; in the absence of such relationships, DOE R&D may not make a major contribution to commercial technology development." As a large fraction of Federal funds for superconductivity is going to these laboratories, this is a worrisome comment, but this is a worry that I will not address in this article.

Contributions to high T_c

The field of high-T_c superconductivity was created by the discovery of new materials. The first high-T_c materials were derived from $(La,Ba)_2CuO_4$; their critical temperature was initially near 30 K but was later raised to 40 K. Discovery of superconductivity in this class of materials was followed by the synthesis of the so-called 1-2-3 compounds, with T_c near 90 K; the bismuth compounds, with T_c up to 106 K; and the thallium compounds, with T_c up to 125 K. For each new class of materials, there was an initial discovery of a compound with a high T_c that resulted in worldwide research activity. This follow-up research, among other things, determined the crystal structure of the superconducting compound, optimized the critical temperature (the first high-T_c bismuth superconductor had a T_c of only 85 K, and the first thallium superconductor a T_c of only 105 K) and pointed out important physical and chemical properties such as the sensitivity to oxygen content, normal-state resistivity and critical fields. (See PHYSICS TODAY, April 1987, page 17, and April 1988, page 21.) I present my view of these events in the above table, in which I have listed the organizations where the initial discoveries were made and also some of those that moved rapidly to take advantage of the discoveries and were therefore involved in the follow-up work.

I realize that drawing up any such table is a good way to alienate many readers, as they will certainly disagree with my lists. My purpose, however, is not to list all the laboratories around the world that made important or interesting contributions, but to try to determine whether US industry was represented among the players. I doubt that many people will question the placement of IBM, AT&T, Bellcore and Du Pont in the table, even though some might wish to add other contributors. Japanese industrial laboratories, conspicuously absent from the table, would certainly appear in a more extensive version.

What do I conclude from my table? First, as everyone knows, the field was created by a European laboratory of a US company. The reasons for this will keep us speculating for years, especially since IBM is unlikely to publish a revealing history of what happened when, where and why. That the breakthrough occurred at IBM Zurich illustrates, I think, the success of the IBM Fellow position, which allows a scientist unusual research freedom in an industrial laboratory. My colleagues at Bellcore, however, regard the success of the IBM research laboratory in Zurich as demonstrating the advantage of having a laboratory well separated from the center of corporate control.

The second conclusion I draw from the above table is that none of the subsequent discoveries of materials with progressively higher T_c's were made at an industrial laboratory. I do not know whether this is reasonable or was to be expected, because I have no knowledge of the research effort dedicated to the search for new materials at industrial laboratories other than my own. But when I compare Bellcore's program with that at the universities of Alabama, Houston and Arkansas, I find that Bellcore has placed much greater emphasis on the exploration and optimization of the properties of existing materials,

Oscilloscope developed and marketed by Hypres uses Josephson junction electronics for high-speed sampling. The oscilloscope has a bandwidth of 70 GHz, which is more than three times larger than the bandwidth of a typical nonsuperconducting oscilloscope. Hypres is based in Westchester, NY. (Courtesy Hypres.)

whereas the university programs have emphasized the search for new materials. Research publications of different groups clearly illustrate this difference in research directions.

Third, the table shows that the US industrial laboratories have been major contributors to the follow-up research. This seems logical, given their generally more extensive instrumentation capability and the freedom of their largely independent investigators to change research directions rapidly, in contrast to universities, where students have thesis projects to complete. It is also interesting and noteworthy that only a small number of US industrial laboratories has been contributing at the leading edge of this field. I will show this more clearly later when I discuss conference attendance.

Consortia

We can learn much about industrial research in the US and Japan, and the influence of government on this research, by examining the largest joint program in each country.

To my knowledge, the only consortium for research in superconductivity in the US is the one formed last year at Microelectronics and Computer Technology Corporation. Its formation, achieved entirely by the efforts of a few talented individuals with extensive experience in superconductivity, was not without difficulties. Those who initiated the idea, I believe, were selling their own talents as much as the concept of joint research. Of course, while they visited the various industrial laboratories to raise support, their own research was at a standstill. (My university friends tell me that obtaining funds from Washington is similarly demanding of their time, but students do carry on in their absence! Anyone who disagrees that obtaining funds has become a problem should examine the total cost of the proposal-and-review process for NSF's new Science and Technology Centers and compare this cost with the disposable funds.)

The MCC consortium was supported by 13 companies in 1987, each of which contributed \$100 000. What will happen to MCC next year is uncertain and depends largely on the consortium's performance in 1988—a situation that may be illustrative of US industry's short-term expectations from research. One company (Du Pont) has already withdrawn, but negotiations are under way with other companies that might join in the future. As is fairly common in US industrial research, the MCC consortium is already requesting Federal support for research.

By contrast, the largest consortium in Japan is the International Superconductivity Technology Center (ISTEC), backed by the Ministry of International Trade and Industry (MITI). It is open to companies worldwide, but so far only three outside Japan have joined—IBM, Rockwell and Du Pont. There are two levels of participation—in the center or in the laboratory. Participation in the center requires a \$16 000 initial donation and \$16 000 per year subsequently; participation in the laboratory, which requires a \$780 000 donation initially and \$94 000 per year subsequently, allows member companies to send two scientists at the company's own expense to carry out joint research at the center's laboratory. The variety of companies represented in the current membership is most revealing. Certainly, many US equivalents of the Japanese companies that have joined, such as those in the railroad, steel and banking industries, have shown no interest in superconductivity.

Of the 88 member companies, 44 have joined at the laboratory level. This guarantees an initial funding of \$35 million, and \$4.8 million thereafter if membership stays constant. A new laboratory is expected to open in October of this year, with Shoji Tanaka, until recently a professor at the University of Tokyo, as deputy president. Among the research themes for the new laboratory will be oxide materials, nonoxide materials, processing technology, theory and ceramics. Assuming that each of the 44 "laboratory" companies sends two scientists (again, at its own expense), the staff could very soon exceed the 100 projected for 1989. I believe it is likely that this laboratory will have the largest research program in superconductivity in the world by 1990, and depending on the coordination and direction its leadership provides, it has the potential to outperform any industrial laboratory in the US. But at present it has a staff of only a few, so it does not affect my analysis of the current situation. The probability that such a powerful joint effort will ever be created by American industry I judge to be zero. However, I could be surprised, as a number of major integrated circuit manufacturers have joined together and created Sematech. Federal support was necessary to make this happen, but MITI is similarly influential in the creation of

Meeting publications, by type of institution

	Industry[1]	Government[2]	University[2]
ASC 1986			
US	46.1 (28%)	68	53
Japan	14 (19%)	58	
All other	3 (5%)	62	
Total	63.1	241	
LT18			
US	17.5 (16.2%)	27.7	62.8
Japan	32.1 (14.3%)	34.3	158.3
All other	3.5 (1.7%)	73.2	128.1
Total	53.1	135.2	349.2
MMS–High T_c			
US	27.6 (26%)	19.8	58.1
Japan	15.6 (22%)	14.9	41.5
All other	26.1 (4.7%)	288.6	244.7
Total	69.3	323.3	344.3
APS March 1988			
US	118 (24%)	97 (20%)	279 (56%)
ASC 1988			
US			
Low T_c	48.8 (29%)	58.7	62.0
High T_c	16.5 (21%)	25.7	35.5
Japan			
Low T_c	15.2 (29%)	15.2	21.2
High T_c	11.5 (32%)	7.25	17.75
All other			
Low T_c	1.3 (1%)	46.5	43.8
High T_c	2.0 (3%)	33.75	34.1
Total	95.3	187.1	214.35

[1] For each country, the percentage of total papers from industry is given.
[2] The "Government" and "University" categories were combined for ASC 1986, except for US papers.

Japanese consortia.

I find the literature from ISTEC fascinating. For example, consider these statements, which I have lifted from that literature, of the center's goals and objectives:

▷ "To undertake various research and studies directed to the superconductivity technology, international exchange programs, as well as basic research in this promising, but still rudimentary, technology."

▷ "Contribute to the development of the world economy, through efficient implementation of research and harmonious development of this technology."

▷ "Dedicated to the international sharing of benefits from advanced superconductivity research."

▷ "ISTEC supports a growing world consciousness, wherein we realize that by running alongside each other we can all cross the finish line together."

I doubt that anyone in the US, whether from the government, universities or industry, could write such statements for any joint program in this country. I also wonder what the implications of the final quotation will be if our Japanese colleagues have to wait for us to catch up as the "finish line" is approached. But as I can find no evidence that we trail in "the race" at present, such thoughts of course simply reflect my negativism about our own capabilities, which, as I have already discussed, we all seem to share.

Attendance at meetings

Another way to find some hard data on the relative level of involvement in superconductivity by various organizations and countries is to examine contributions to various conferences—in particular, to count publications in proceedings. I have had this done for five major conferences—the 1986 Applied Superconductivity Conference, the 18th International Low Temperature Physics Conference in 1987, the 1988 Materials and Mechanisms of Superconductivity/High-T_c Superconductivity meeting, the 1988 March meeting of The American Physical Society and the 1988 Applied Superconductivity Conference. I chose these meetings because they represent a cross section of established conferences that emphasize recent science and technology rather than speculations about future applications and markets.

The papers presented at the meetings have been counted by source, that is, by whether the work reported was done at an industrial, government or university laboratory. Because of some uncertainty about the source of funding for "institutes" in some countries, the numbers for government laboratories and universities might be slightly inaccurate, but the percentage of papers from industry for a given country should be reliable. For publications whose authors were from different organizations, I assigned an equal fraction of a point to each contributing organization. For example, a paper coauthored by five persons from three companies counted as one-third of a publication from each company.

1986 Applied Superconductivity Conference. This meeting was held in Baltimore in October 1986, two months before the news of the Zurich discoveries broke. It was one of a series of such meetings that have been organized and run by a group of enthusiasts in applied superconductivity since 1966. The emphasis in these meetings is on applications, and more basic papers are often excluded. In the proceedings of these meetings is collected by far the most comprehensive picture available anywhere of the growth of superconductivity applications. These proceedings are also the only publications in which the status of both the large-scale (that is, magnets) and small-scale (that is, electronics) applications is discussed. The 1986 meeting represented a low point in the field, but there was a ceremonial session that is fascinating historically. As we were remembering the good old days of low T_c, high-T_c superconductivity had already been discovered, but nobody in the audience knew about this discovery. The session included talks commemorating 75 years of superconductivity, 50 years of the London theory, 25 years since the discovery of materials that have high values for both the critical current density and the critical magnetic field, 25 years of the Josephson effect and 20 years of the meetings themselves.

The ASC has remained a US meeting; it has never been held abroad. International attendance has grown over the years, however, and 45% of the papers in 1986 were from foreign sources. (As I will show later, there seems to be a willingness on the part of our foreign colleagues to travel to the US that we do not reciprocate in our attendance at conferences abroad.)

I had my first surprise in this analysis of meetings when I compared, separately for the US, Japan and all other countries, the number of talks given by researchers from industry with the number given by government laboratory and university workers. I had believed that Japanese research, especially that presented at an applied superconductivity conference, was carried out primarily in industrial laboratories. But the belief turned out to be wrong, as the table on page 42 shows: The percentage of the total Japanese papers that were from Japanese industry was smaller than that of the US papers from US industry.

The second surprise was that, when averaged over all countries, 79% of the research in applied superconductivity was being carried out at government laboratories and universities, and hence only 21% at industrial laboratories. One might say that this was *before* the discovery of high-T_c superconductivity, but when one remembers that this was also 26 years after the discovery of high-critical-current materials and 24 years after the discovery of the Josephson effect, it is disconcerting to see how little involvement there was in this meeting by industry worldwide. I could perhaps argue that superconductivity has remained a research field, even after all these years.

The results for US industry became even less satisfying when I examined the number of contributions from the various laboratories (see the table on the right). The larger number of papers from IBM reflects to some extent IBM's earlier large program in Josephson computers, which was funded partially by Federal agencies. I believe that the research at Westinghouse, the next on the list after IBM, was also partly (or perhaps even largely) funded by Washington. (It is important to differentiate between the industrial research paid for by the company itself from its revenue flow and that done on contract and paid for by the defense agencies. The former requires commitment of the company's revenues; the latter may be regarded simply as increased revenue, and it implies that the funding agency believes in the eventual value of that technology more than the company does.) After IBM and Westinghouse, the contributors include two relatively small companies specializing in superconducting products—Hypres and Intermagnetics General.

18th International Low-Temperature Physics Meeting. LT18 was held in Kyoto, Japan, in August 1987, about nine months after the 1986 Materials Research Society meeting in Boston, which marks the beginning of the high-T_c activity worldwide. It was a major scientific meeting with a large fraction of superconductivity papers, whereas previous meetings in the series were more evenly balanced among liquid helium, metals, superconductivity and low-temperature techniques.

Again, I found the analysis of the papers published in the proceedings quite surprising (see the table on page 42). First, the fraction of papers from industry was very similar for the US (16%) and Japan (14%), whereas it was almost zero for other countries (2.5 of the 3.5 papers not from the US or Japan were from IBM Zurich!). The smaller industry percentages at LT18 compared with those at the 1986 ASC for both the US and Japan reflect the differing emphases of the two meetings—on basic science at LT18 but on applications at the ASC.

Second, the very small number of papers from

Meeting publications by institution[1]

	ASC 1986	LT18	MMS-High T_c	APS March 1988	ASC 1988	
					Low T_c	High T_c
US industry[2,3]						
Allied-Signal	—	—	—	2	—	—
AT&T	2.3	4.5	6.4	38	—	1.5
Bechtel	—	—	—	—	3.0	—
Bellcore	1.5	1	1.5	10	—	3.0
Cryopower	—	—	—	—	2.0	—
Du Pont	—	—	1.5	5	—	—
Exxon	—	—	—	5	—	—
Ford	—	—	1	4	—	—
General Dynamics	2.5	—	—	—	2.5	—
GM	—	—	—	2	—	—
Hypres	4.5	—	—	—	5.0	—
IBM	10.2	8.8	11.3	37	5.8	2.0
Intermagnetics	2.8	—	—	—	—	—
Oxford	1	—	—	—	3.0	—
Rockwell	—	—	—	2	—	—
Sperry	2.5	—	—	—	4.0	—
Supercon	1.5	—	—	—	4.0	—
Teledyne	1.5	—	—	—	1.3	—
TRW	3	—	—	—	4.3	1.5
Westinghouse	8.1	—	2	3	9.0	3.0
Xerox	—	—	1	4	—	—
Japanese industry						
Fuji	—	—	1		—	—
Fujitsu	1.0	—	—		4.0	—
Furukawa	—	—	—		—	2.5
Hitachi	2.5	2.5	1.3		—	—
Idemitsu Kosan	—	1.5	—		—	—
JEOL	—	1	—		—	—
Kawasaki	1.0	—	—		1.0	—
Kobe Steel Co.	1.2	—	—			—
Matsushita		1	1.3		—	—
Mitsubishi	—	3	—		1.5	—
NEC	2	—	1.8		1.0	—
Nippon Steel	—	1	1		—	—
NTT	2	12	4.6		—	—
Res. Dev. Corp.	—	—	—		2.0	—
Sanyo	—	1	—		—	2.0
Sharp	—	1	—		—	—
Sumitomo	—	1.5	1		—	—
Toshiba	1.7	3.7	—		3.5	—
Other countries						
Asea Brown Boveri			5.9			
Bergen Scientific			1			
Balzars AG			1			
IBM (Zurich)			7.7			
Philips			3.7			
Plessey			1			
Siemens AG			3.5			
US government labs						
Ames		5	2	4.1	—	1.0
Argonne		9	2.5	17.0	1.5	3.0
Brookhaven		—	1.9	12.2	6.8	1.0
CEBAF		—	—	—	6.0	—
Fermilab		—	—	—	6.0	—
Lawrence Berkeley		1.3	2	2.5	8.5	—
Lawrence Livermore		—	1.5	3.8	6.5	—
Los Alamos		3.3	5.6	17.2	—	3.0
NASA		—	—	1.0	—	—
NBS		2	1	7.7	10.0	4.5
NCSC[4]		—	—	—	3.5	1.0
NOSC[5]		—	—	2.0	—	1.0
NRL		3.5	1.8	13.2	3.3	7.8
NSA		—	—	1.0	—	—
NSWC[6]		—	—	1.0	—	—
Oak Ridge		1.5	—	—	3.5	2.0
Sandia		1	—	3.5	—	—

[1] Dashes stand for less than 1 or no contributions. Blanks indicate groups for which the analysis was not carried out.
[2] Cryogenic Design, Physical Dynamics and Nolovac Cryogenics contributed 1 paper each to ASC 1986.
[3] Biomagnetic Technology, Fusion Power, GE, Hewlett-Packard, Hughes and Physical Dynamics contributed 1 low-T_c paper each to ASC 1988. American Superconductor and Hughes contributed 1 high-T_c paper each to ASC 1988.
[4] Naval Coastal Systems Center.
[5] Naval Ocean Systems Center.
[6] Naval Surface Weapons Center.

industry in other countries indicates that only the US and Japan have industrial laboratories working at the frontier of basic research in this field.

Third, the US representation was largely from IBM, with a secondary presence from AT&T (see the table on page 43). The lack of representation from other US industrial laboratories seems to imply a certain nonchalance toward foreign research activity in this field. The Japanese industrial representation, meanwhile, was spread over many more companies, but it must be noted that this meeting was held in Japan.

Fourth, the US representation—from industry, Federal laboratories and the universities—was 20% of the total at this international meeting, whereas that from Japan at the 1986 ASC (nominally a US meeting) was 24%. The US government laboratories were quite well represented compared with US industry.

Materials and Mechanisms of Superconductivity/High-T_c Superconductivity. This meeting, held in Interlaken, Switzerland, in the beginning of March 1988, was again one of a series organized by enthusiasts in the field. The series was begun in 1971 in Rochester, by David Douglass, under the title "d and f Band Superconductors," but in 1982, following the first meeting of the series to be held outside the US, the series was renamed Materials and Mechanisms of Superconductivity. Its expanded title for 1988 was accompanied by a very large increase in attendance, from a few hundred at Ames, Iowa, in 1985, to 1150 this year. It is primarily a science meeting, with only a few talks devoted to applications.

Analysis of the proceedings (see the tables on pages 42 and 43) seems to confirm the pattern of the earlier meetings. Industry contributed 26% and 22% of the papers from the US and Japan, respectively, compared with only about 5% from industry in other countries. (Of the 26.1 papers from other countries, 7.7 were from IBM Zurich.) Participation by industry from both the US and Japan was significantly above that at LT18 in Kyoto, reflecting perhaps the less fundamental nature of the meeting, or perhaps the industry's growing interest in high-T_c superconductivity. The dominance of IBM and AT&T is clear: The two when combined represent well over half the US industrial effort and roughly equal the contribution of the US government laboratories. The government laboratories seem to be noticeably underrepresented at this meeting compared with the others I have discussed.

1988 March meeting of The American Physical Society. The March meeting is the major condensed matter physics meeting of the APS. It has grown significantly in recent years: The total number of talks presented at the meeting has risen from 2424 in 1985 to 3080 in 1986 and 3345 in 1988. It is a domestic meeting; papers, excluding those that are invited, must either be by APS members or be sponsored by a member.

While the growth in the March meeting has occurred partly at the expense of other APS meetings, particularly the annual meeting held in January, the very large increase in the number of papers presented is a datum that should be considered seriously by those who seem to attend the meeting largely to complain that research funding is insufficient or has not increased in recent years. The growth of the meeting, roughly at the rate of 300 papers per year, was not noticeably affected by the discovery of high-T_c superconductivity.

The number of sessions (each session consists of either about 16 contributed talks or about 4 or 5 invited talks) devoted to superconductivity was 12 in 1985, 13 in 1986, 16 in 1987 and 64 in 1988. Clearly a large number of condensed matter physicists have changed their research interests from other fields to superconductivity.

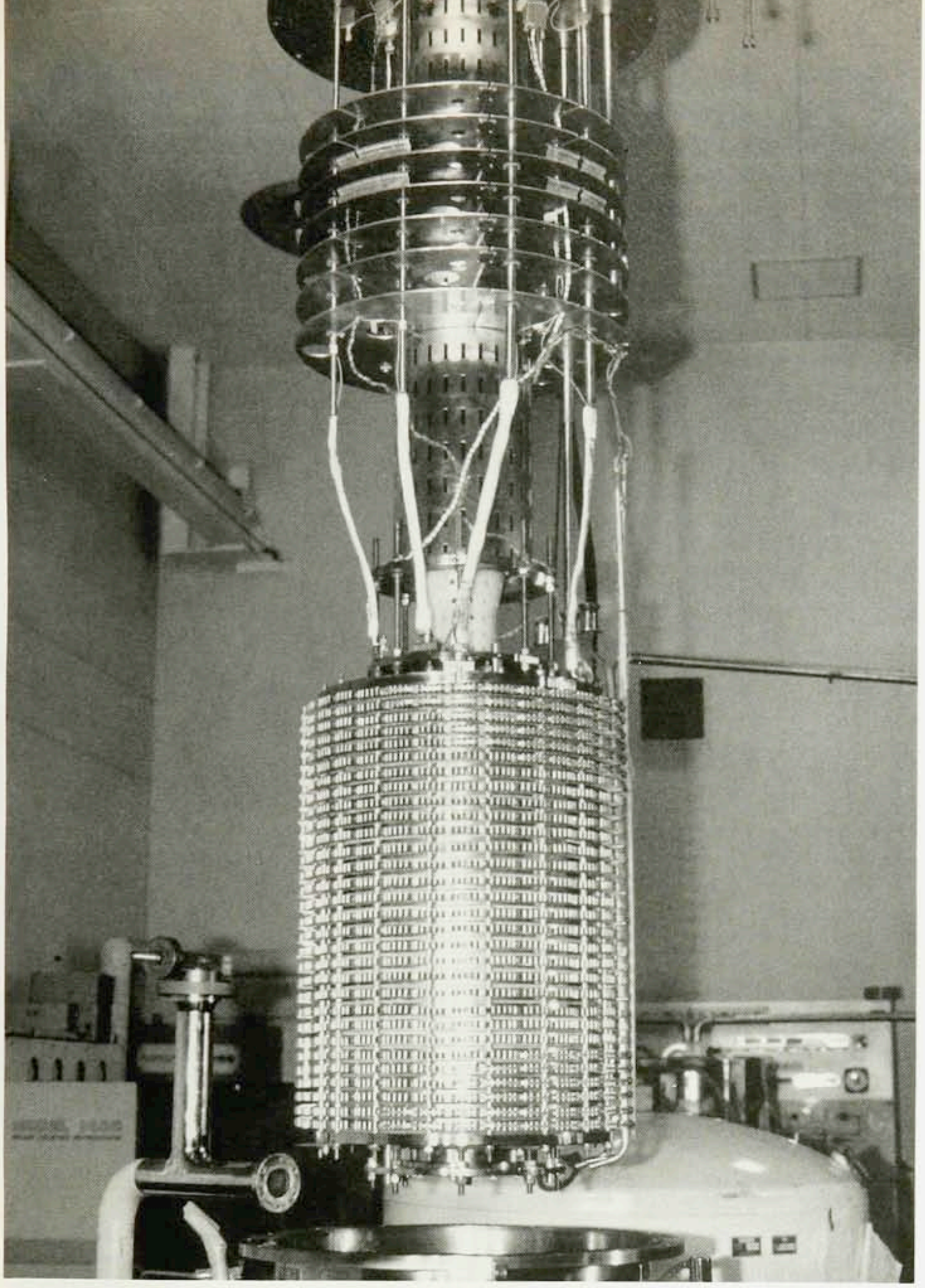
Of the 64 sessions on superconductivity in 1988, 60 were devoted to high T_c. This number must be compared with the one postdeadline evening session on high T_c one year earlier. The staggering level of activity cannot be reconciled with comments, such as "There's no money going into superconductivity," that I heard at the 1988 meeting. US industry accounted for 24% of the talks presented at the meeting, government laboratories 20% and universities 56%. (In the table on page 43, I give the numbers only for the US, as this is purely a US meeting.)

One interesting result that emerges from the analysis of the four meetings I have discussed so far is that despite the explosion of interest in superconductivity created by the discovery of high-T_c materials, there is no evidence for any radical change in the balance of research effort among industry, the government laboratories and the universities, especially if one allows that the ASC was an applications meeting and hence of more interest to industry and to the government laboratories. The US industry participation remained around 25% in these four meetings.

Data on the talks by industry scientists at the March meeting (see the table on page 43), when combined with those from the other meetings, confirm a suspicion I have been harboring for some time, namely, that the US industrial research effort is being carried out by two companies. However, the extent of their dominance came as a surprise to me. It is probably very similar in many other technical fields.

The government laboratories' contribution at the meeting was roughly equal to that of the two major industrial laboratories, but there was a reasonable balance in the relative number of contributions from the four major Federal centers.

The small number of papers from what may be called the "second team" of industrial laboratories prompts the following question: If we argue (incorrectly, perhaps) that AT&T and IBM do not need technology transfer from other US institutions because they are largely self-sufficient, and if we exclude Bellcore as a recipient of technology because the telephone companies are not allowed to manufacture, then the number of talks representing the knowledge base being generated in this field is 376. This knowledge is to be utilized by the rest of the US industry, which was represented by 33 talks. This



Superconducting magnet. This magnet was sold by Intermagnetics General to a high-field research facility in Japan. The magnet uses an inner coil wound from V_3Ga and an outer coil wound from Nb_3Sn. The material for the inner coil was made in Japan, but the magnet was designed and fabricated in the US. (Courtesy Intermagnetics General.)

seems to illustrate, although in a somewhat simplistic way, one of the problems in the US science and technology environment, namely, that our science is excellent but falls on deaf ears in industry, at least in the civilian sector.

ASC 1988. This year's Applied Superconductivity Conference, held in San Francisco in August, presents us with an opportunity to study the effect of the discovery of high-T_c materials on research in applied superconductivity. The attendance at this meeting was significantly higher than at the 1986 meeting. The meeting program lent itself to a neat division into two parts—one dealing with the progress in commercializing niobium-based materials, and the other with the initial attempts to create devices and conductors from the high-T_c materials. A majority of the papers in the latter category described the synthesis and processing of thin films and the fabrication of SQUIDS. I have analyzed the proceedings of the meeting with reference to these two categories—low T_c and high T_c.

There is little surprise in the overall analysis (shown in the tables on pages 42 and 43). The US industrial participation continues to be about 25% of the total US contributions, but while the US industrial participation in low T_c is remarkably close to that in 1986 (about 29%), only 21% of the US high-T_c papers are from US industry. Meanwhile, the Japanese industrial participation, about 30%, has increased to the highest level of all the conferences studied, but industry in other countries once again contributed very few papers.

The real surprise, which I sensed at the meeting, is in the sources of the US industrial publications, which are listed in the table on page 43. The major players at the APS meeting are now conspicuous by their absence. For example, AT&T, Du Pont and Bellcore presented no papers on conventional materials, because none of them have ongoing programs in applications of those materials. Even more striking is the absence of Du Pont and GE from the contributors of high-T_c papers and the fact that AT&T presented only 1.5 papers.

The dominance of AT&T and IBM at the APS March meeting and their almost negligible presence at this applications-oriented meeting are open to any number of fascinating interpretations. But I will refrain from pointing them out, as I still have friends at both laboratories.

The government laboratories were well represented at this meeting. Apparently, in the US, applications of superconductivity are still largely being pursued in the government laboratories and at universities.

Some counterarguments

Although the analysis of consortia and meetings does not support the generally gloomy view that the US cannot compete in superconductivity, it does not lead to great optimism either. I believe, however, that there are several positive signs of US competitiveness.

First, I hear rumors that US industry is building larger research programs than are presently reflected in its presentations at meetings. (Those given to pessimism might argue that Japanese industry does not publish its research results as readily as US industry, and hence using publications in the above analysis underestimates the Japanese programs. In my view, superconductivity still demands active materials research and its applications so far have been rudimentary; hence scientific publications are probably a reasonable measure of activity.) My best guesses for the numbers of scientists working in superconductivity at industrial laboratories in the US are as follows: AT&T and IBM each have between 70 and 100 scientists; Du Pont about 60; General Electric, Westinghouse and Hewlett–Packard each have about 30 scientists; and Kodak and Bellcore about 20 each. My guesses are based on little more than what the rumor mill tells us, but I would be surprised if they are wrong by more than 30%. (A recent newsletter quotes a much higher number for Westinghouse, however.) More accurate numbers are being collected by the Office of Technology Assessment for a future report. If my numbers are correct, about 400 persons are involved in superconductivity research in US industry, with a total investment of about $100 million per year. This probably exceeds the current Federal funding for work in high-T_c materials.

Second, the history of superconductivity shows that in this field the small, new companies have succeeded, the established ones have not. This is encouraging, because the number of new venture capital companies in superconductivity is growing in the US at a surprising rate. We should remember that the first company to sell SQUIDS—SHE, now called Biomagnetic Technologies—was in the US, and that the first instrument to be sold that made use of a circuit of Josephson junctions—the Hypres oscilloscope—is also from the US. Despite the fact that Japan has maintained its Josephson device program, that program has not yet created any products, whereas the Hypres oscilloscope can be traced directly to the IBM Josephson program.

Furthermore, the superconducting magnets in magnetic resonance imaging systems constitute the largest commercial market for superconductivity today. This market was created by small companies in the US and Europe, without any direct Federal involvement, although one could argue that niobium–titanium conductors were improved over the years using Federal funds. A number of US companies also sell high-field research magnets, some of them very competitively in Japan.

Hence there is evidence that relatively small US companies have competed successfully in bringing superconductivity to the marketplace. As long as the market grows slowly, I see no reason why these companies and others that have recently emerged should not be able to compete effectively in the future, as long as the research base in the US stays healthy and the results of this research are available to these companies.

In retrospect, it is fascinating to reflect on the US companies that have invested heavily in superconductivity research and those that now sell products in the marketplace. The former include AT&T, IBM, RCA, GE and Westinghouse; among the latter are Supercon, American Magnetics, GA Technologies, GE, Intermagnetics General, Hypres, SHE and Quantum Design. Of the large US companies only General Electric now sells a product using superconductivity, but its research in this field lapsed for many years until others demonstrated the potential of magnetic resonance imaging. Perhaps the most striking example is Bell Labs, which holds the patents for NbTi and Nb_3Sn superconductors, for the first applications of Josephson junctions, for Nb-Al-Nb metallization for Josephson junctions and for a number of novel circuits. To my knowledge, no profit has ever been realized from these patents. This was partly due to the unusual legal constraints placed on AT&T, but perhaps explains why at least this major US company can be forgiven for viewing superconductivity with a certain suspicion.

What do I conclude from these facts and speculations?

▷ Industrial participation in superconductivity, as judged from publications at conferences, is about 25% of the national effort in the US. This ratio has not changed significantly since the discovery of high-T_c materials. Japanese industrial participation is at about the same level, with perhaps some sign of recent increase. Research contributions to high-T_c from industry in all other countries is very small.

▷ A small group of US industrial laboratories has maintained a commanding presence at the forefront of high-T_c research, but to date these companies appear less interested in applications of these materials. These companies have recently not been active in commercialization of conventional low-T_c materials.

▷ Relatively small US companies have led the march in bringing products using niobium-based superconductors to the marketplace. I expect these companies to remain competitive unless the field grows dramatically. Such growth could be prompted, for example, by a rapid solution to the problem of low critical currents in the high-T_c superconductors or discovery of superconductivity at temperatures above 400 K.

Have I managed to shake my pessimism about the ability of US industry to stay ahead of its competitors as superconductivity moves from basic research to applications and technology? Perhaps. A colleague who recently returned from an ISTEC meeting in Japan told me that speakers there were confidently predicting the construction of a levitated train from Tokyo to Osaka and of a superconducting transmission line in Tokyo, and also foresaw the use soon of superconducting electronics. Meanwhile here in the US the Superconducting Super Collider will use 10 000 superconducting magnets, and I hear that the Strategic Defense Initiative will build an energy storage magnet of 1 km diameter. Superconductivity research in all its manifestations and applications is alive and well in both countries, but in its own way in each.

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This article is adapted from a talk given at the Thirteenth Annual AAAS Colloquium on Research and Development Policy, held in Washington on 14–15 April. The session in which the talk was delivered was titled "Government's Role in Promoting Science and its Commercial Applications: Lessons in Superconductivity." I would like to thank attendees at the AAAS meeting for discussions and comments following my presentation. The analysis of the Applied Superconductivity Meeting was done more recently to make this article timely. My sincere thanks are due to Carol Criss, who carried out the analysis of the conference proceedings, and to Anil Khurana, who edited the text of my talk. ■